GAMMA RAYS IN THE MODERN MULTI-MESSENGER ASTRONOMY ERA

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Physics & Astronomy Colloquium
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GAMMA RAY BURSTS

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Jet collides with ambient medium (external shock wave)

Collapse of a massive star or merger of two compact objects.

Collimated relativistic outflow.

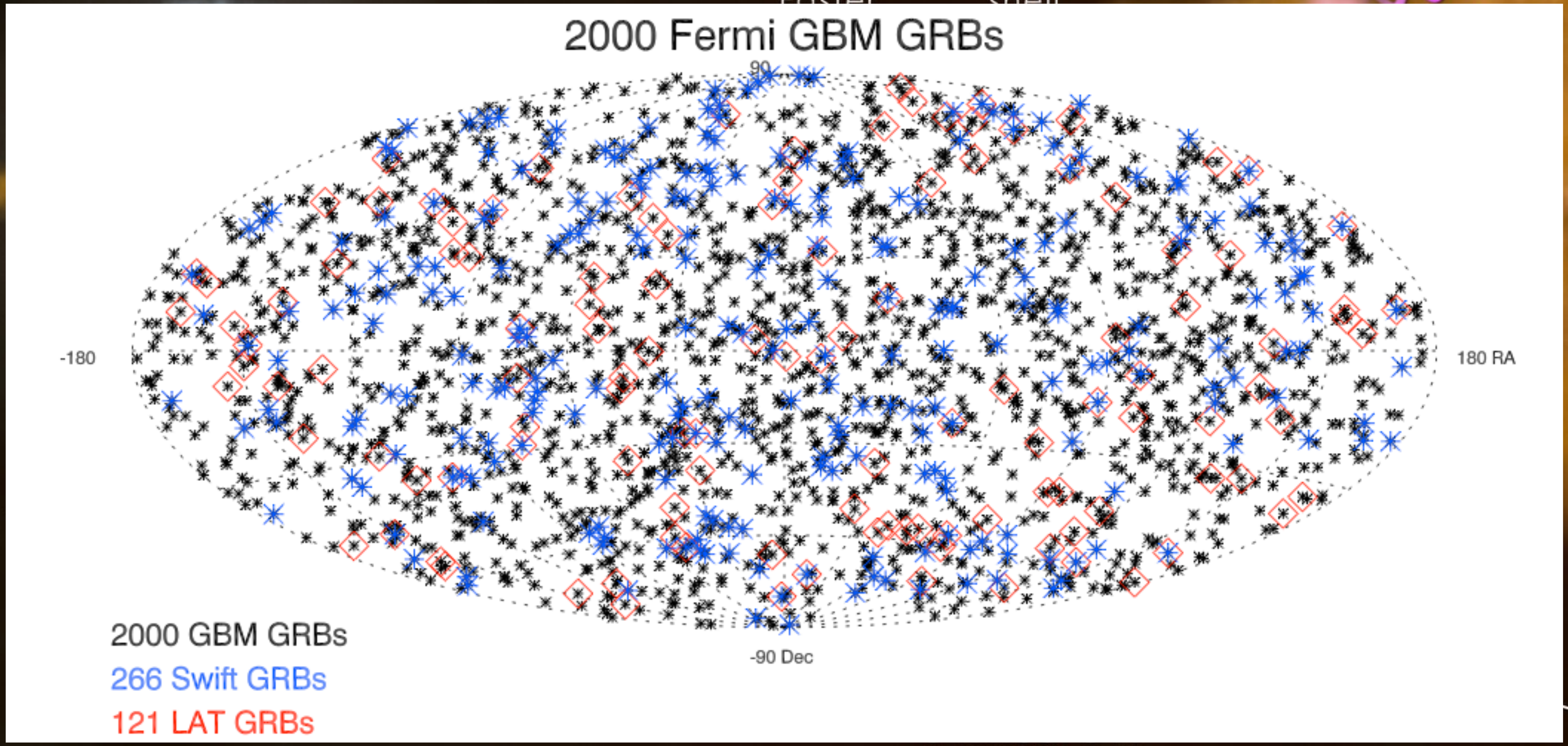
Prompt keV-MeV emission, afterglow in other wavelengths.

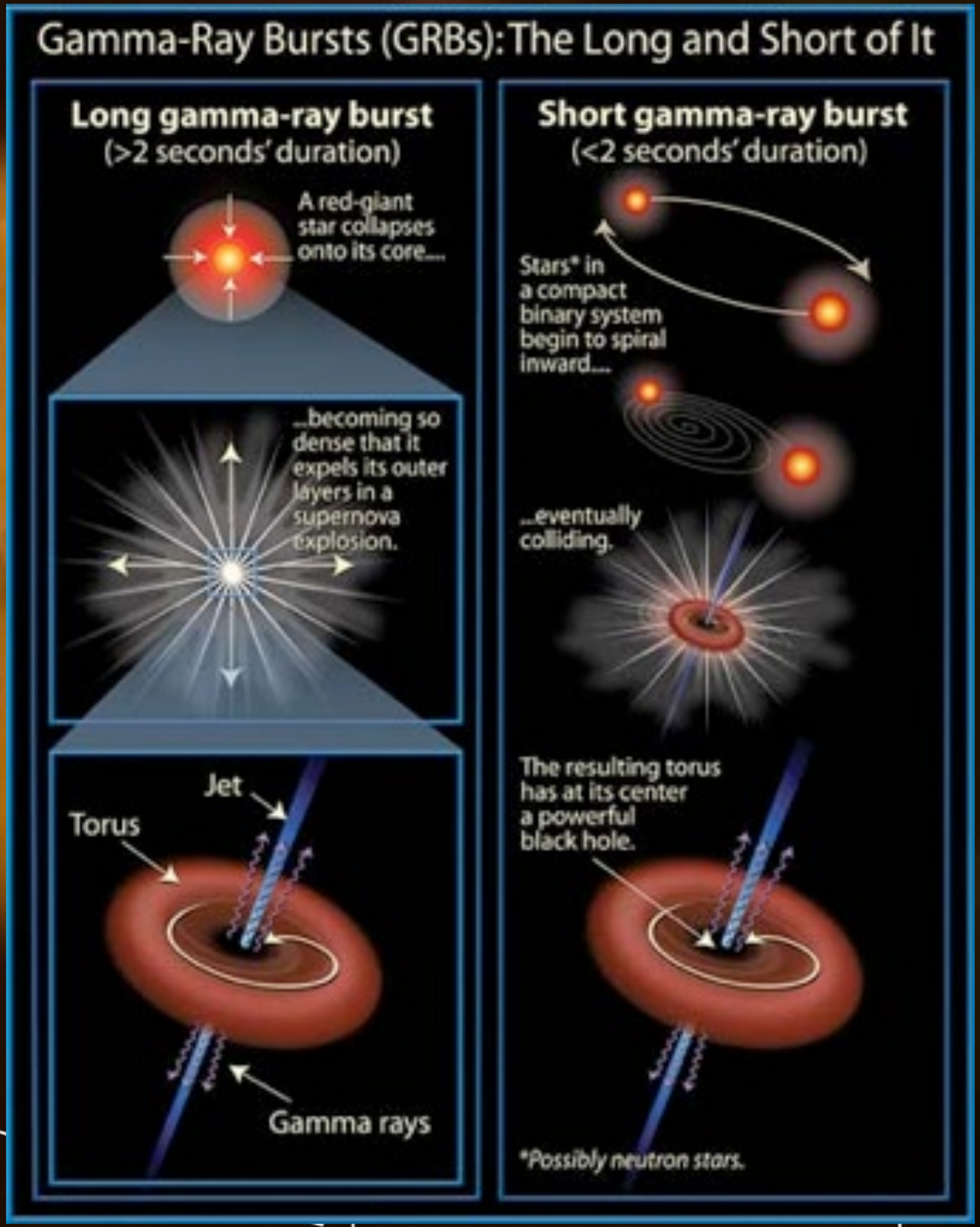
Detected ~ once per day, distributed all over the sky.

Colliding shells emit low-energy gamma rays (internal shock wave)

Slower shell

Faster





Afterglow

GAMMA RAY BURSTS

Jet collides with ambient medium (external shock wave)

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- Collimated relativistic outflow.
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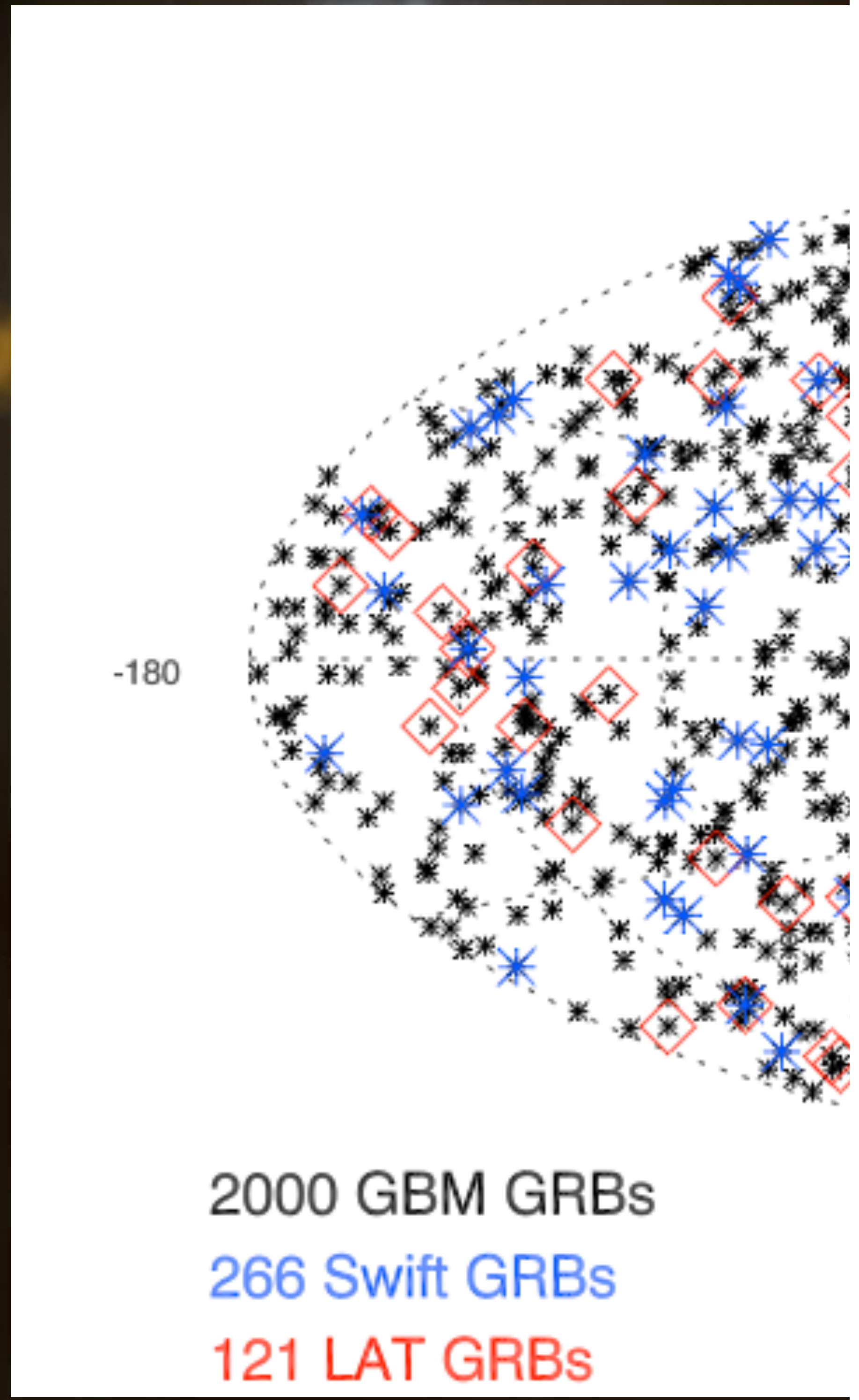
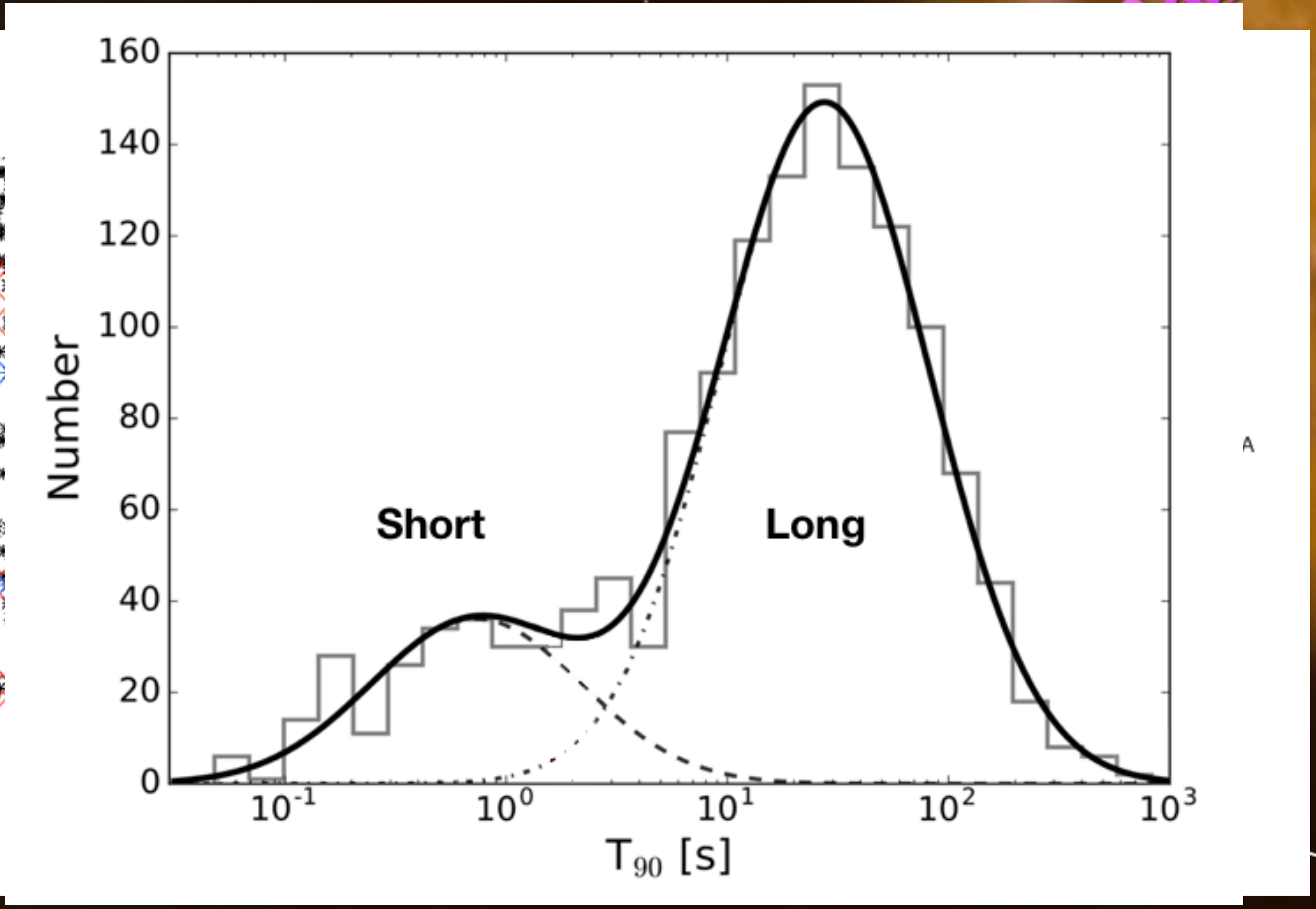
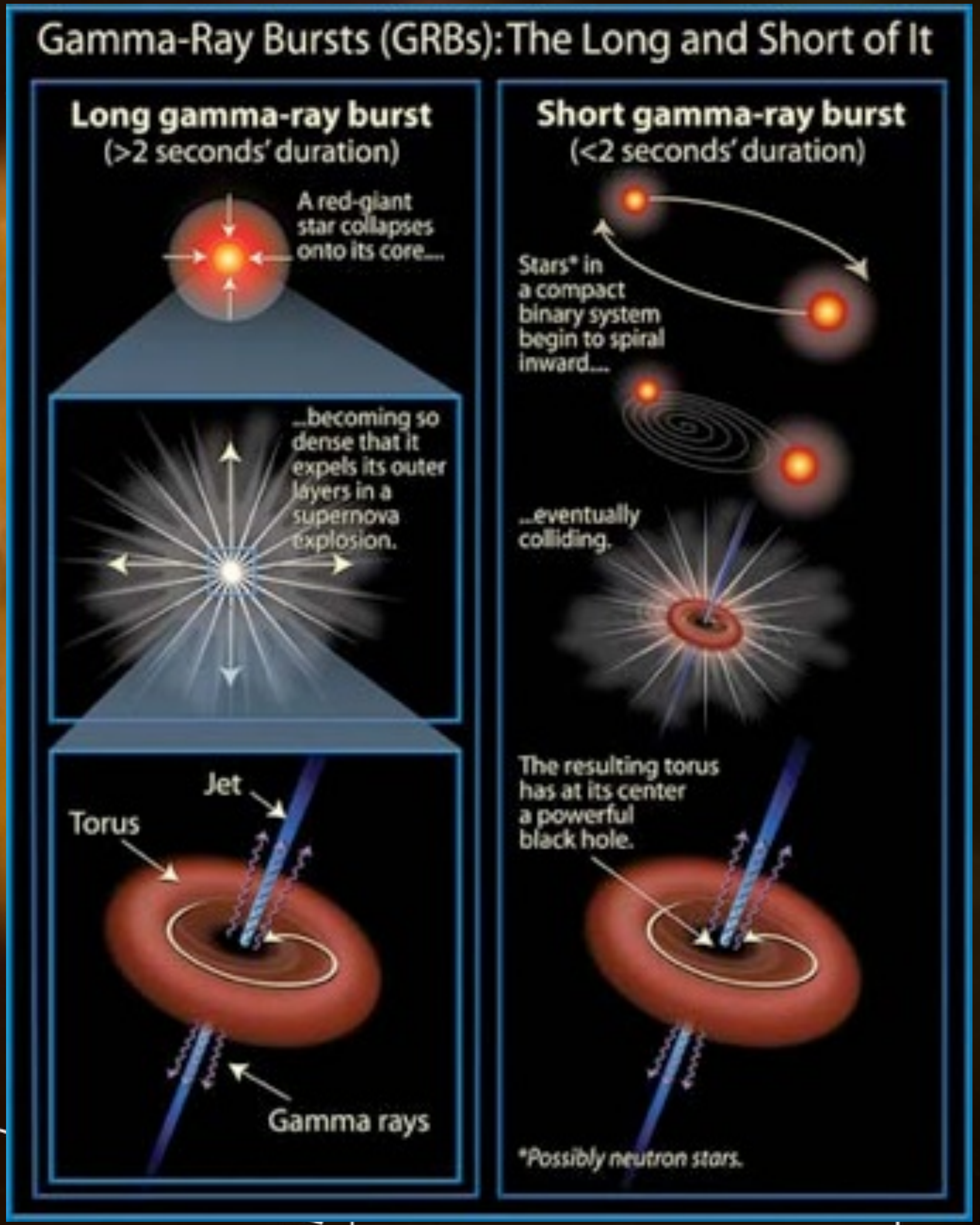


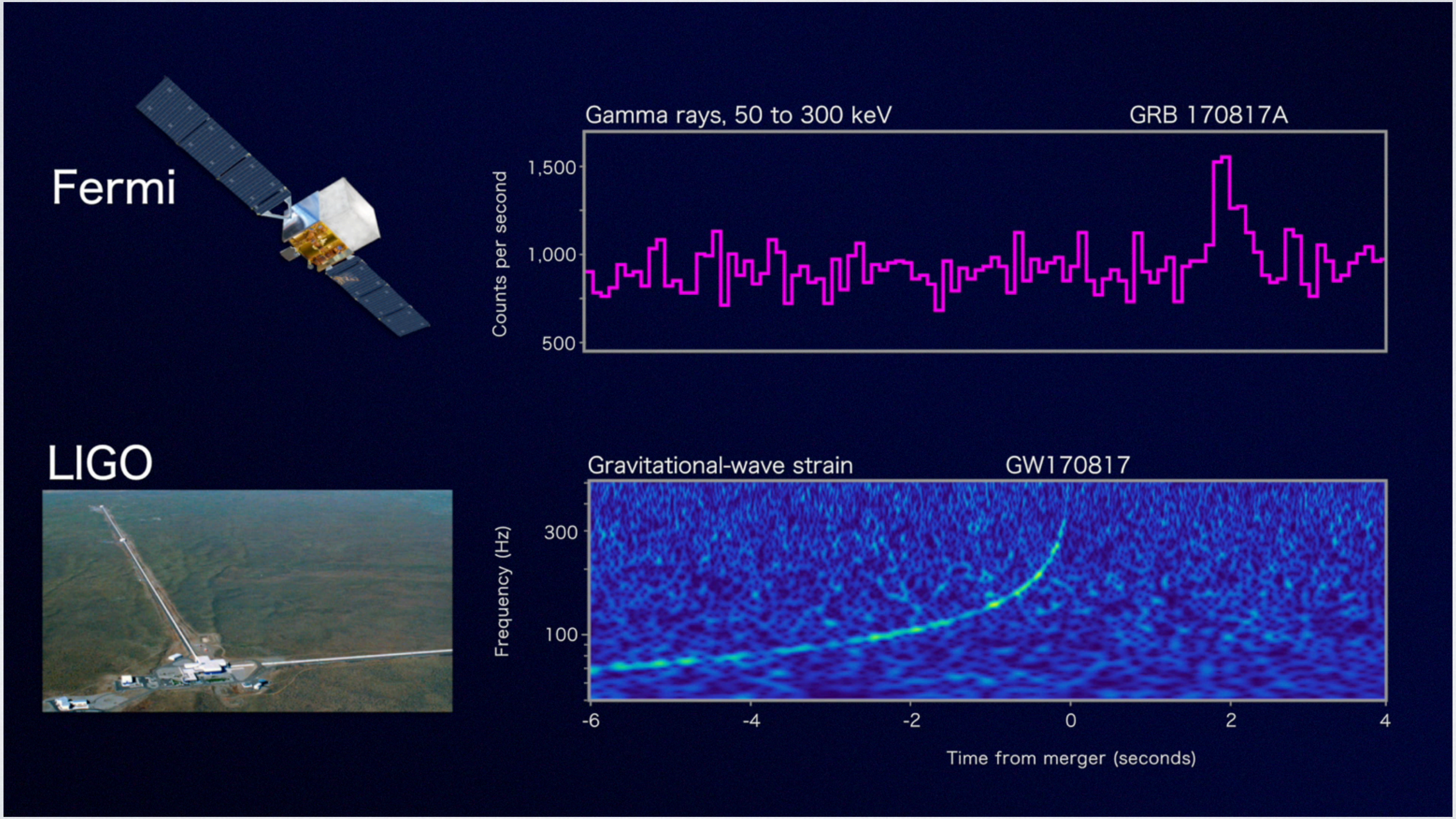




Afterglow

BINARY NEUTRON STAR MERGERS

2017-08-17



Fermi
LIGO
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

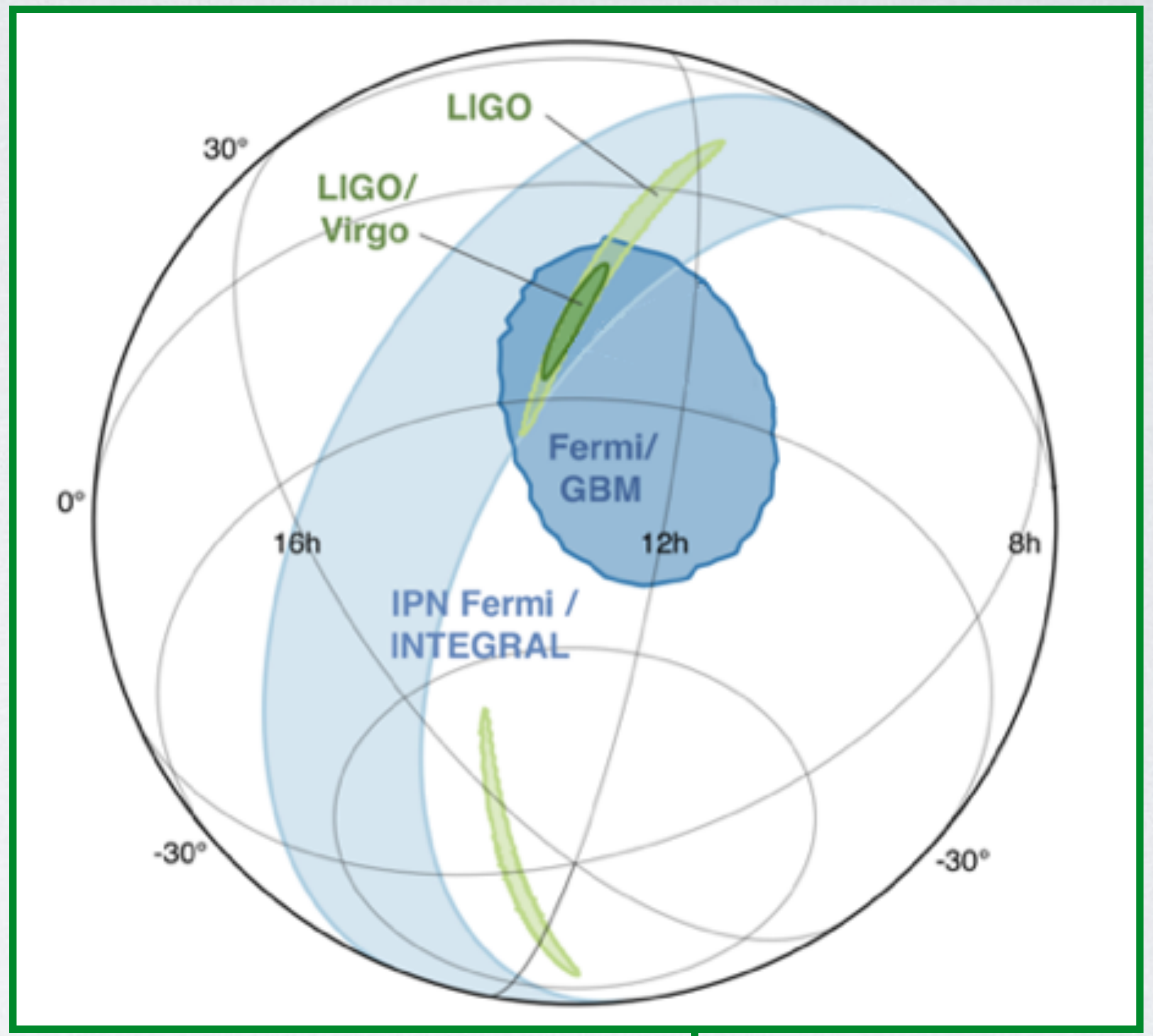
2017-08-17

```
///////////////////////////////////////////////////////////////////////////
TITLE:           GCN/FERMI NOTICE
NOTICE_DATE:     Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE:     Fermi-GBM Alert
RECORD_NUM:      1
TRIGGER_NUM:     524666471
GRB_DATE:        17982 TJD;   229 DOY;   17/08/17
GRB_TIME:        45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF:  4.8 [sigma]
TRIGGER_DUR:     0.256 [sec]
E_RANGE:         3-4 [chan]   47-291 [keV]
ALGORITHM:       8
DETECTORS:       0,1,1, 0,0,1, 0,0,0, 0,0,0, 0,0,
LC_URL:          http://heasarc.gsfc.nasa.gov/FTP/fermi/data/gbm/triggers/2017/
bn170817529/quicklook/glg_lc_medres34_bn170817529.gif
COMMENTS:        Fermi-GBM Trigger Alert.
COMMENTS:        This trigger occurred at longitude,latitude = 321.53,3.90 [deg].
COMMENTS:        The LC_URL file will not be created until ~15 min after the trigger.
```

GBM Alert

First On-board GBM Localization

LIGO Report of coincident GW/ GRB



Joint LIGO/ Virgo sky map

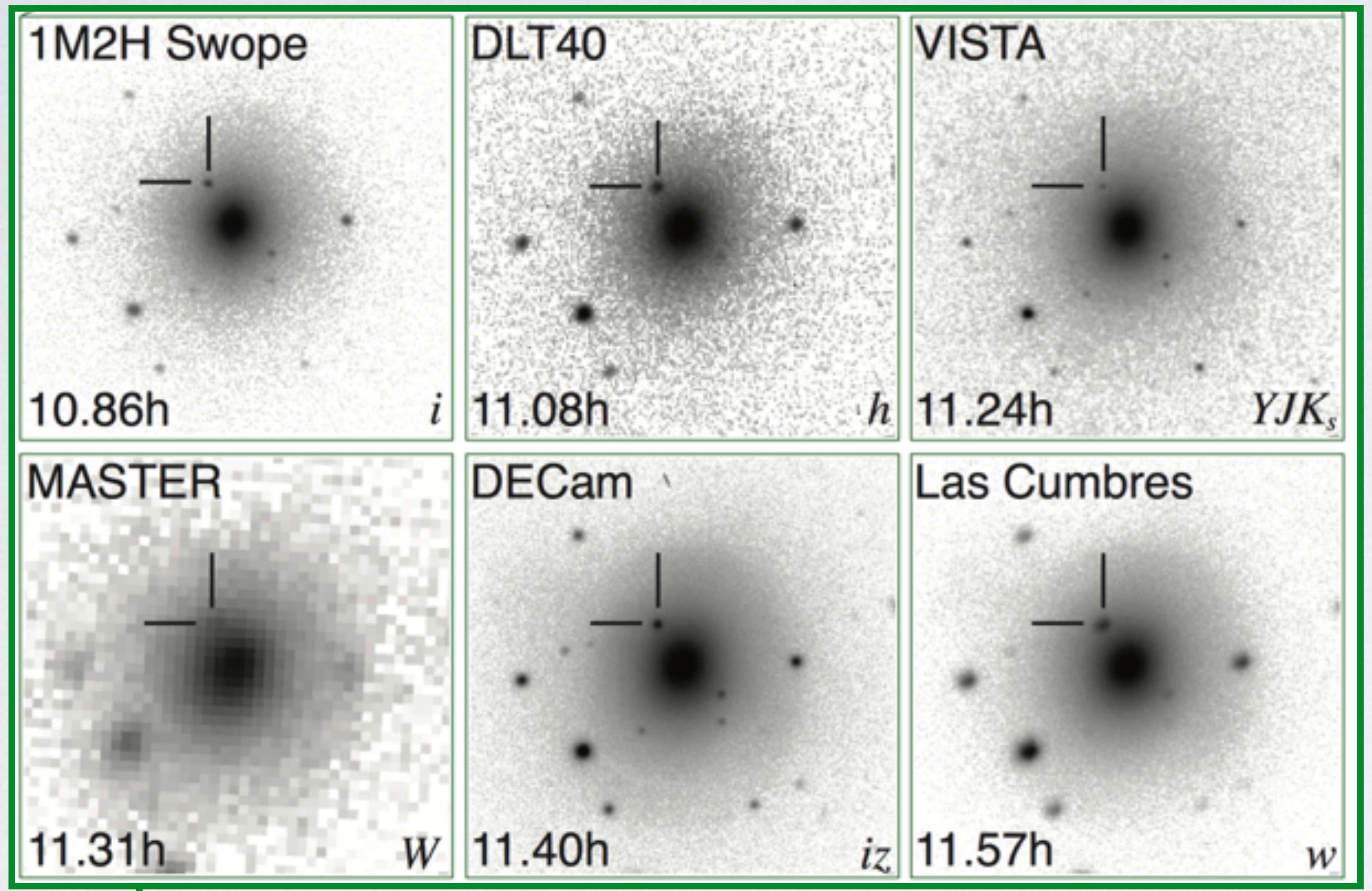
+16 s

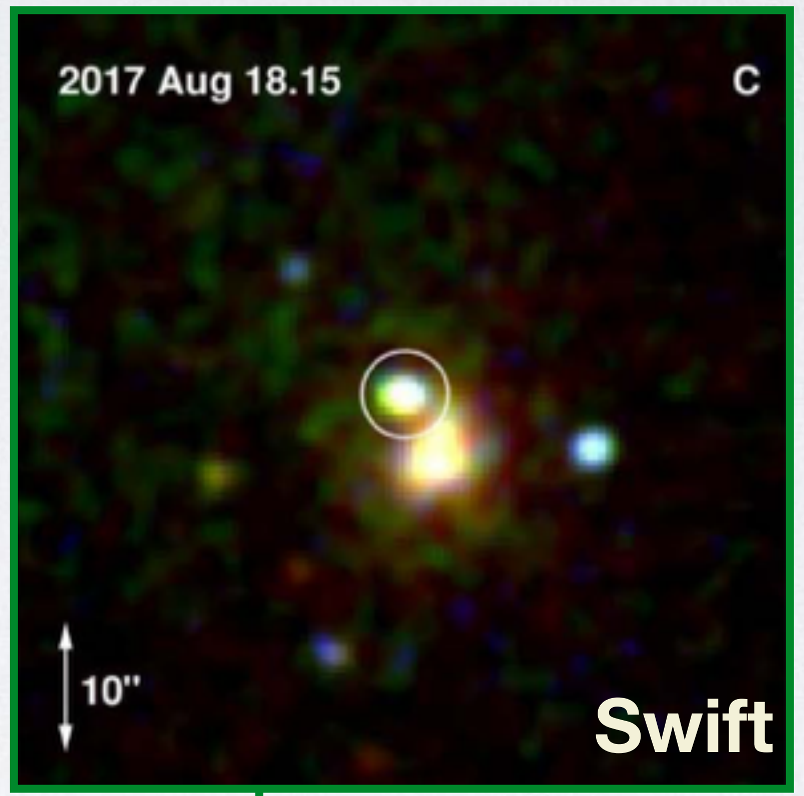
+27 s

+45 min

+5 hour

2017-08-17





Reports of a blue optical transient near an elliptical galaxy NGC 4993 at ~40 Mpc (Abbot et al. 2017).

Discovery credit goes to Smartt et al. (2017) who observed the region with the 1m Swope telescope at Las Campanas Observatory

Swift observations reveal bright UV source, but no evidence of X-ray emission (Evans et al. 2017)

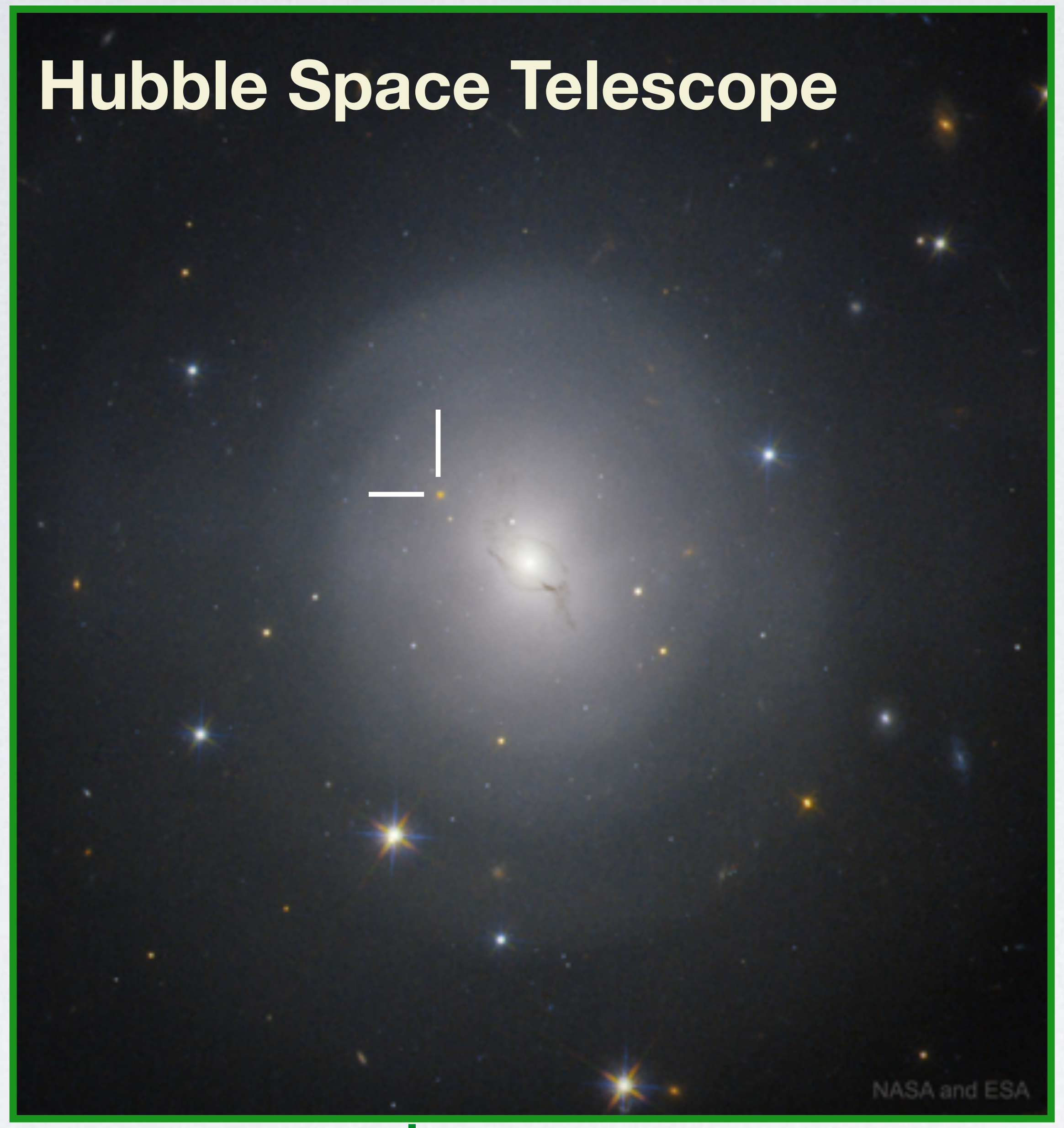
NuStar observations show no X-ray emission (Evans et al. 2017)

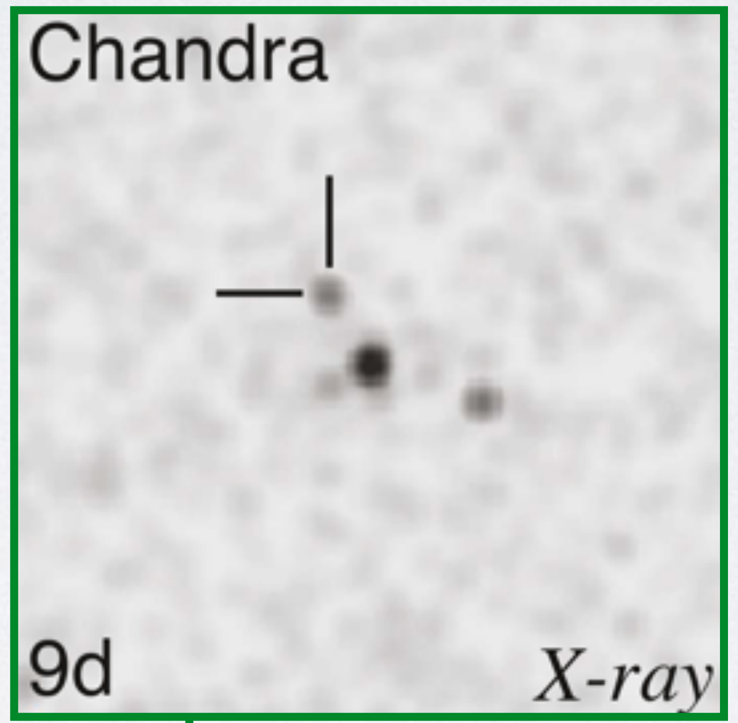
+12 hours

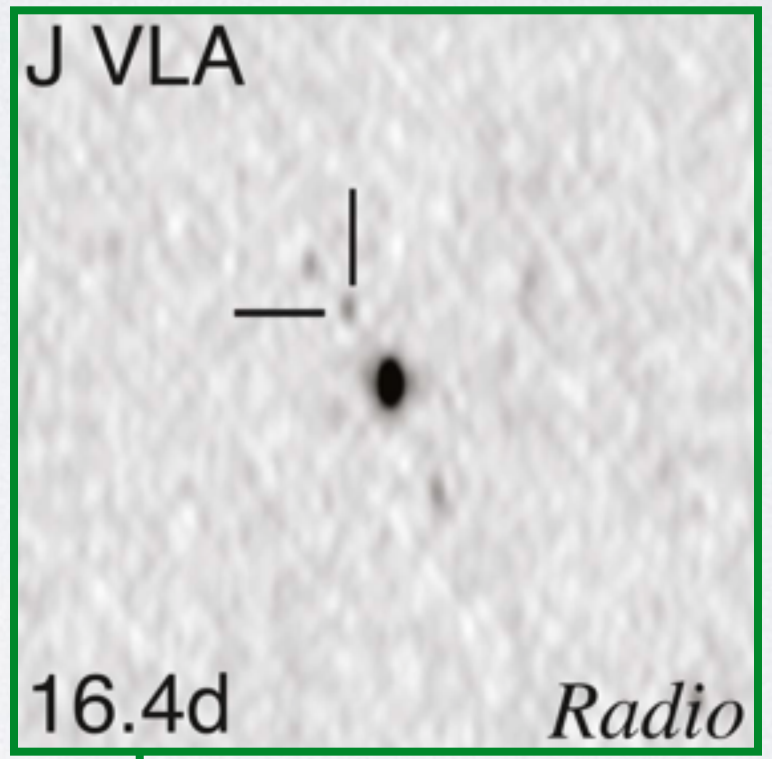
+13 hours

+14 hours

2017-08-17







Chandra observations show no X-ray emission (Fong et al. 2017)

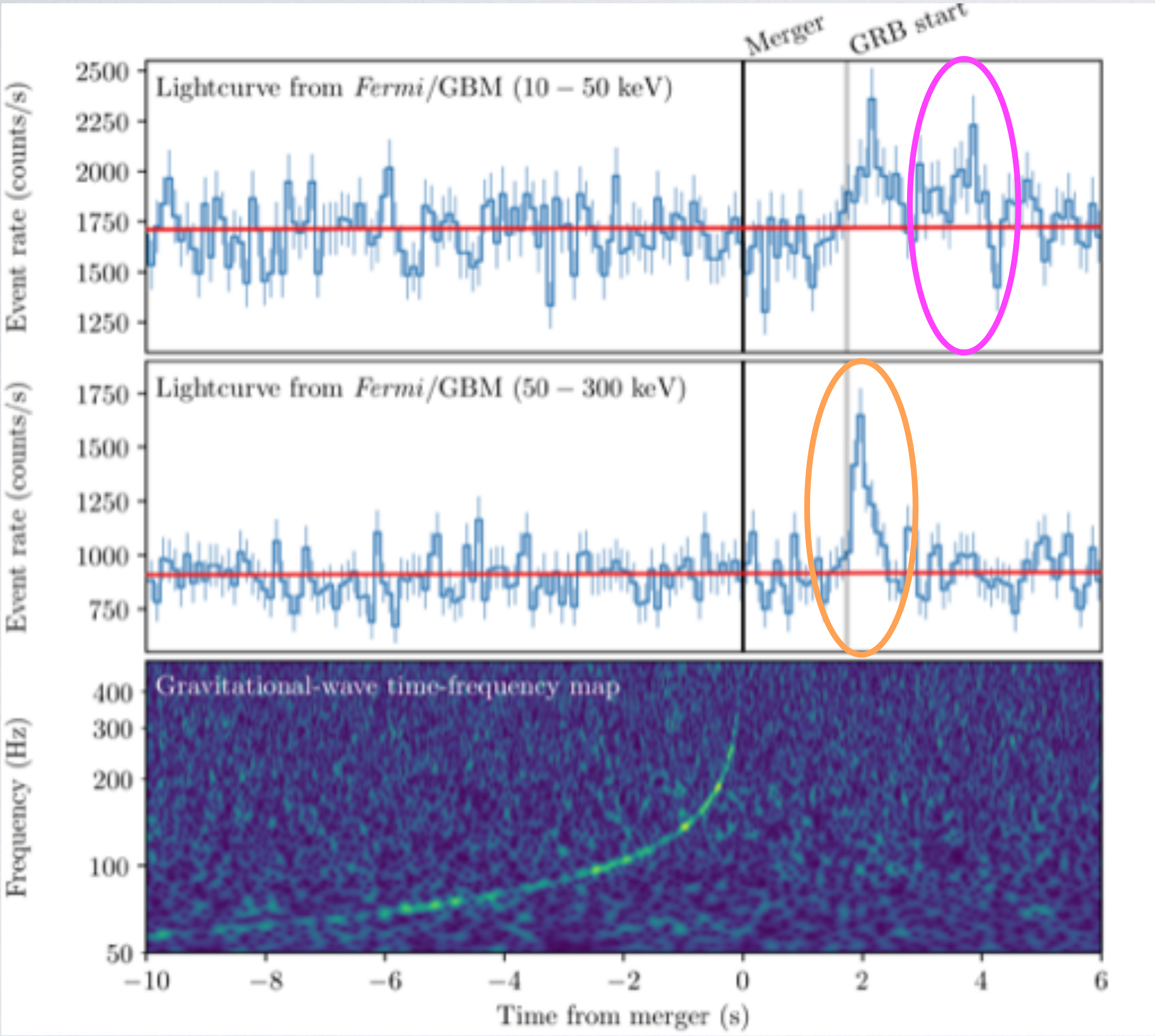
Hubble observations reveal a reddening source (Adams et al. 2017)

Chandra observations reveal first evidence of delayed X-ray emission (Troja et al. 2017)

Radio counterpart reported by VLA (Mooley et al. 2017)

+2 days | +5 days | +9 days | +16.4 days

GRB 170817A / GW170817



Abbot et al. 2017, ApJ, 848, L13

Binary neutron star merger and short gamma-ray burst association confirmed!

- GRB 170817A detected by GBM 1.7s after GW170817, a BNS merger event
  - extensive electromagnetic followup resulting in detection of a kilonova.
  - two components:

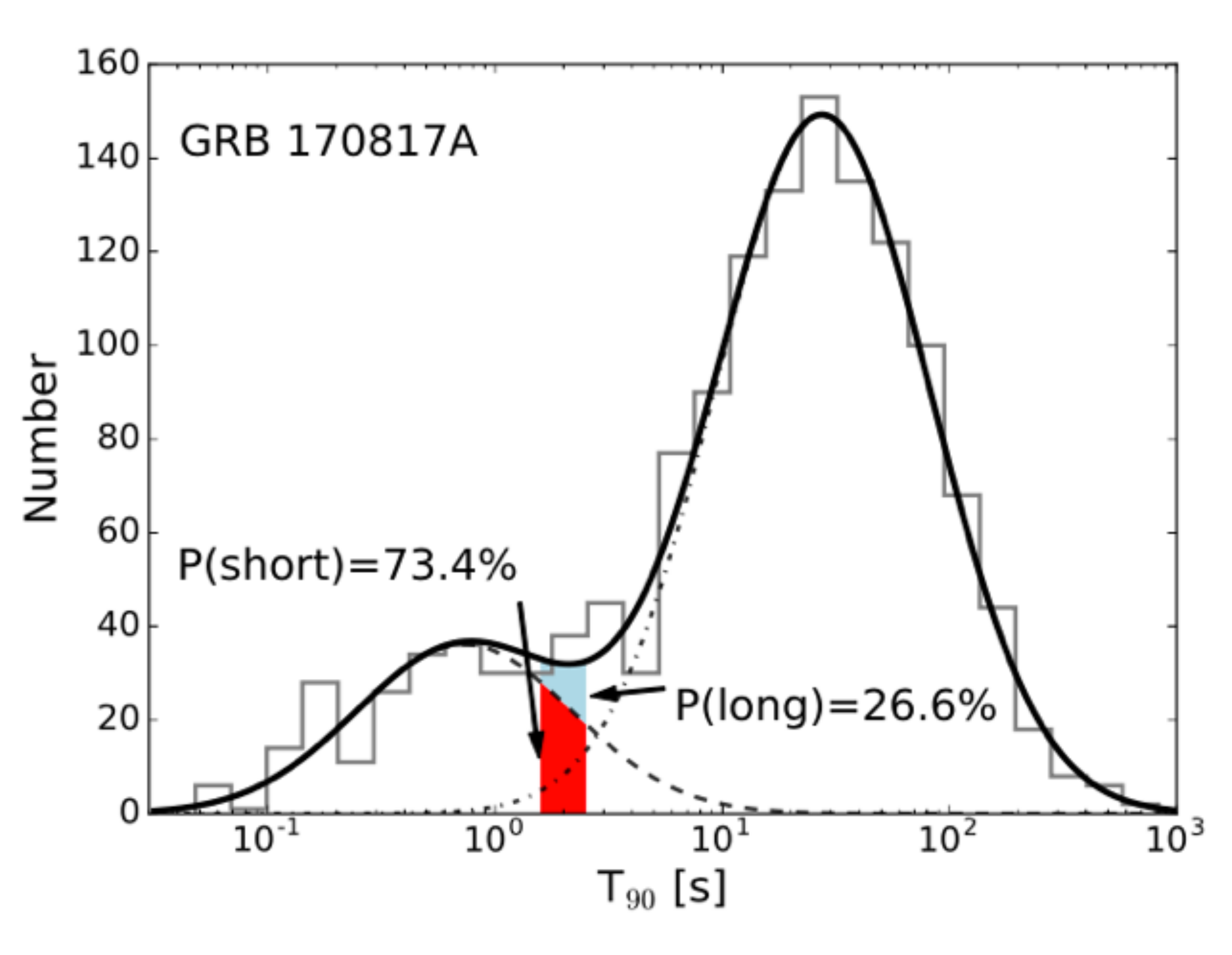
    initial GRB spike — best fit Comptonized model with Epeak 185 keV

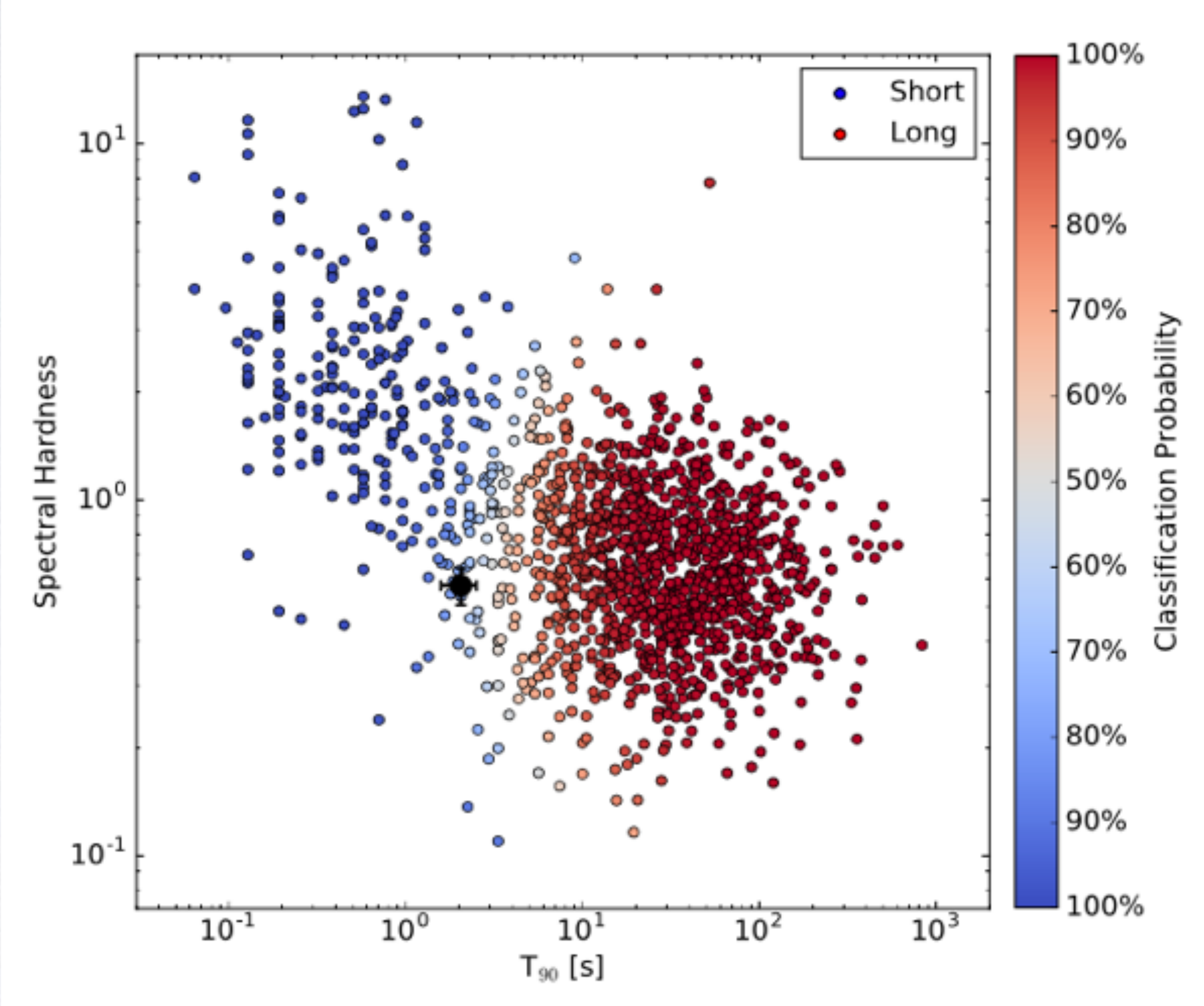
    weak thermal tail — blackbody kT ~10keV

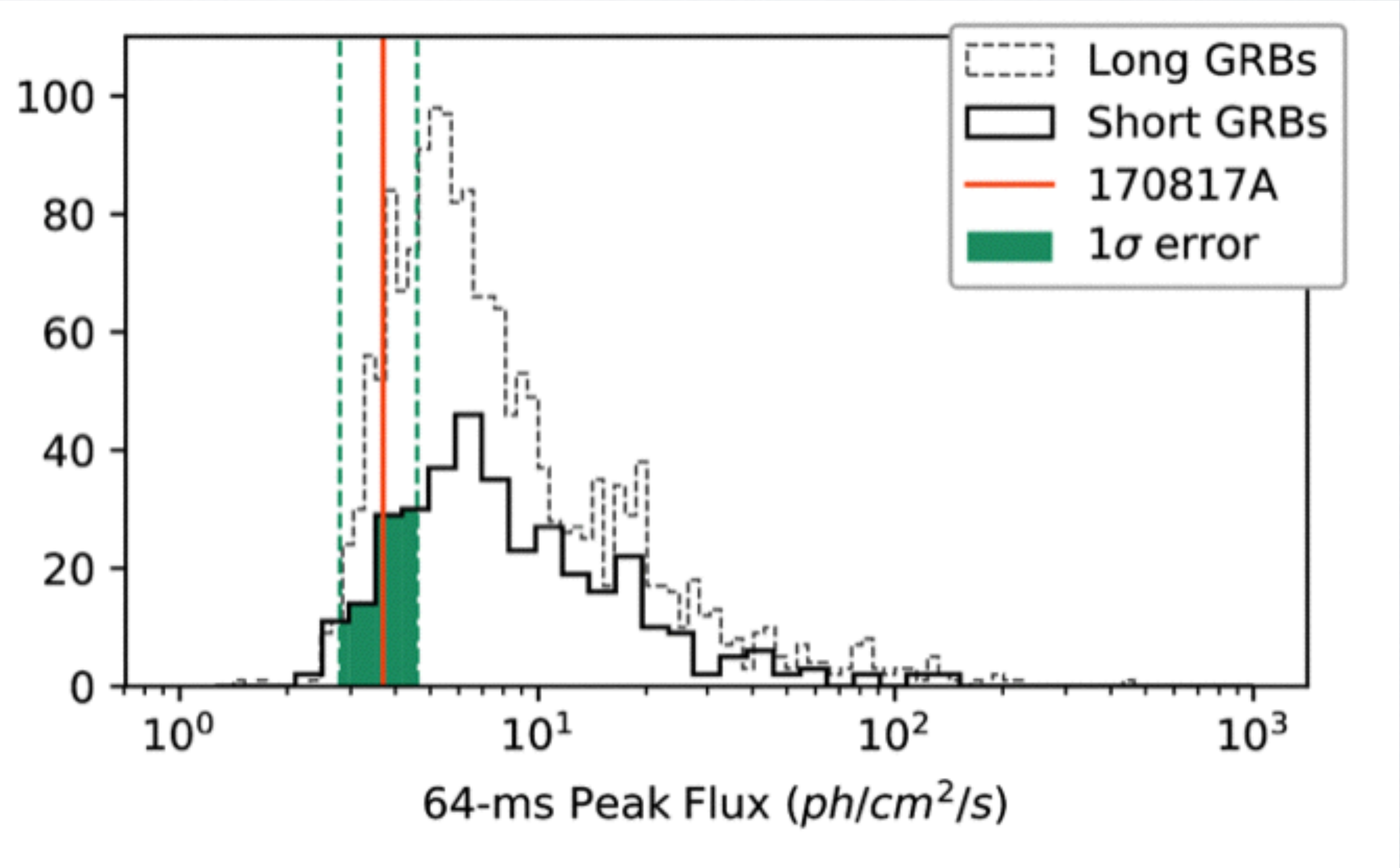
  - joint science:
    - tightest constraint on speed of gravity: gravitational waves and gamma rays travelled 130 million light years and arrived within 2 seconds -> consistent with speed of light within 1e-15
    - constraints on neutron star equation of state
    - open questions: merger and jet geometry, intrinsic properties, population characteristics

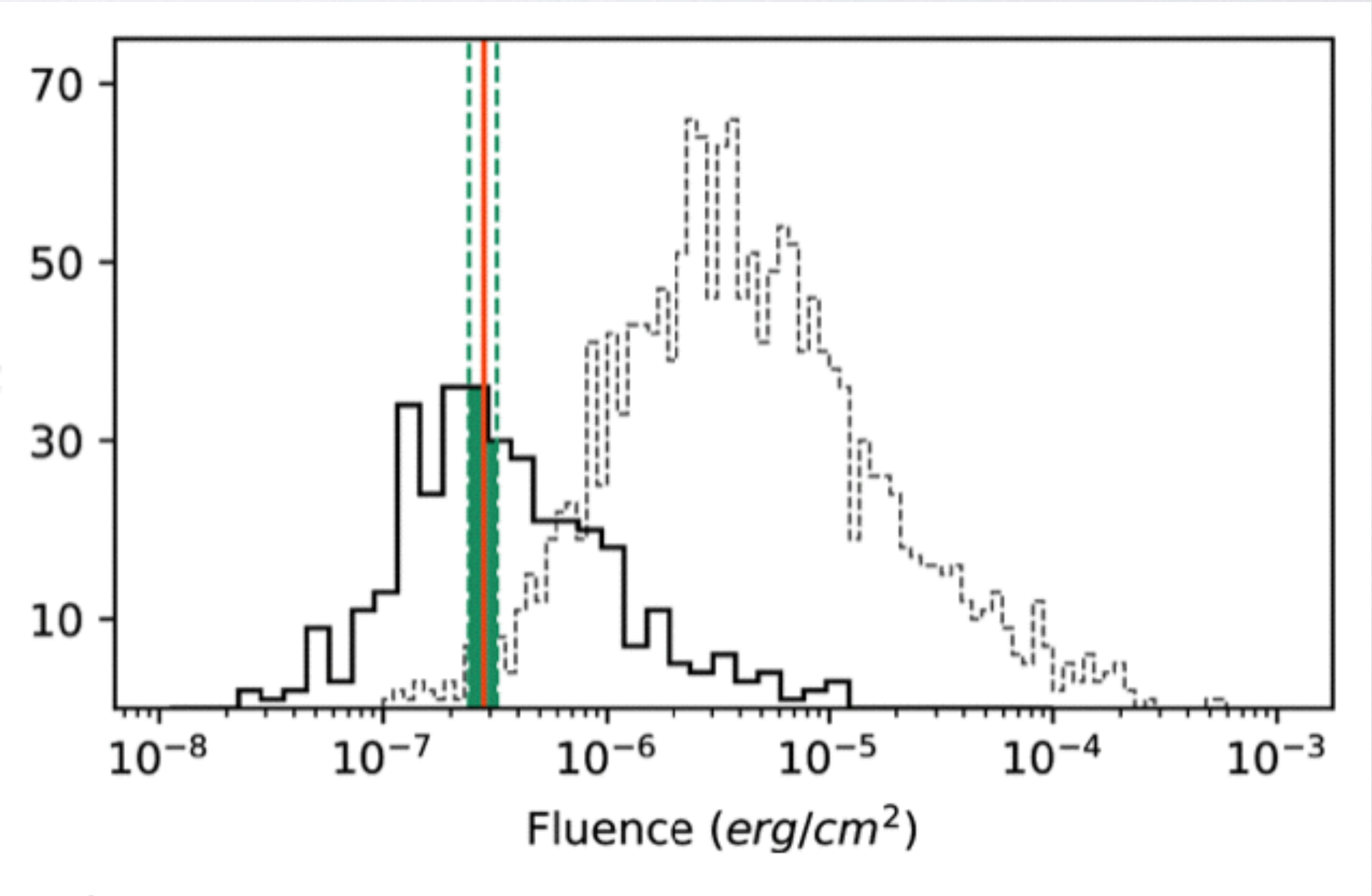
GRB 170817A

GRB 170817A appears to be a typical short gamma-ray burst.



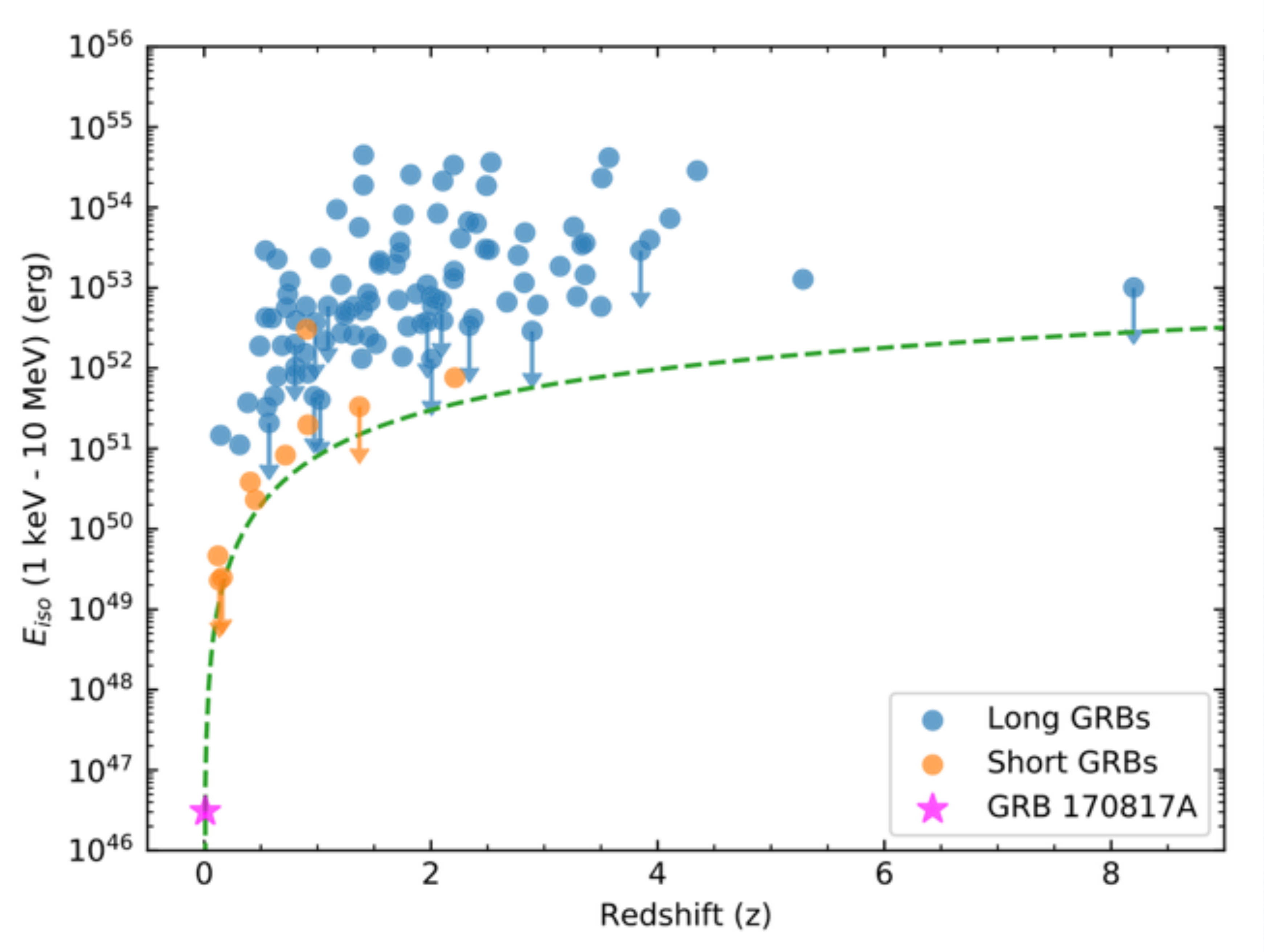


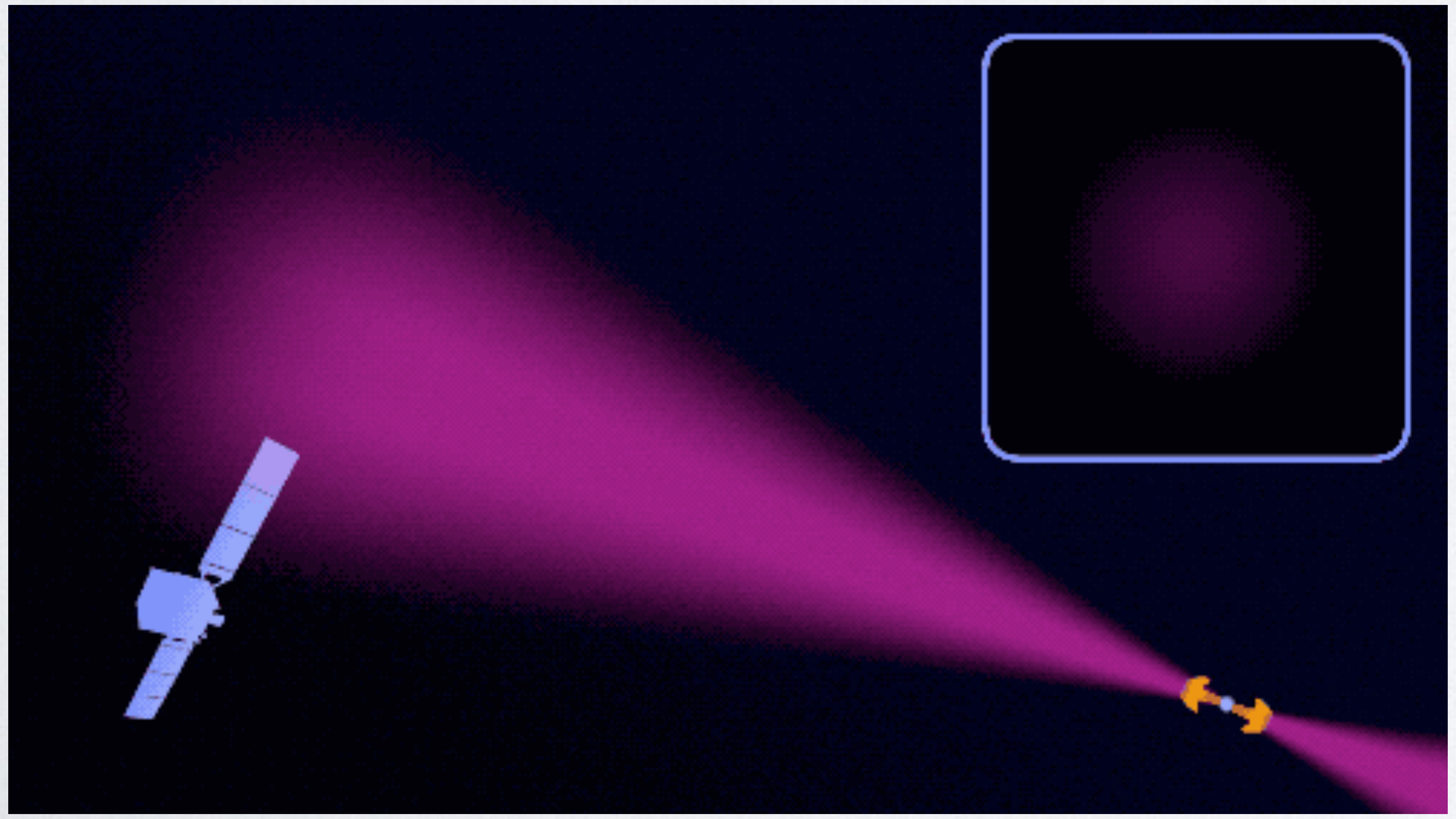




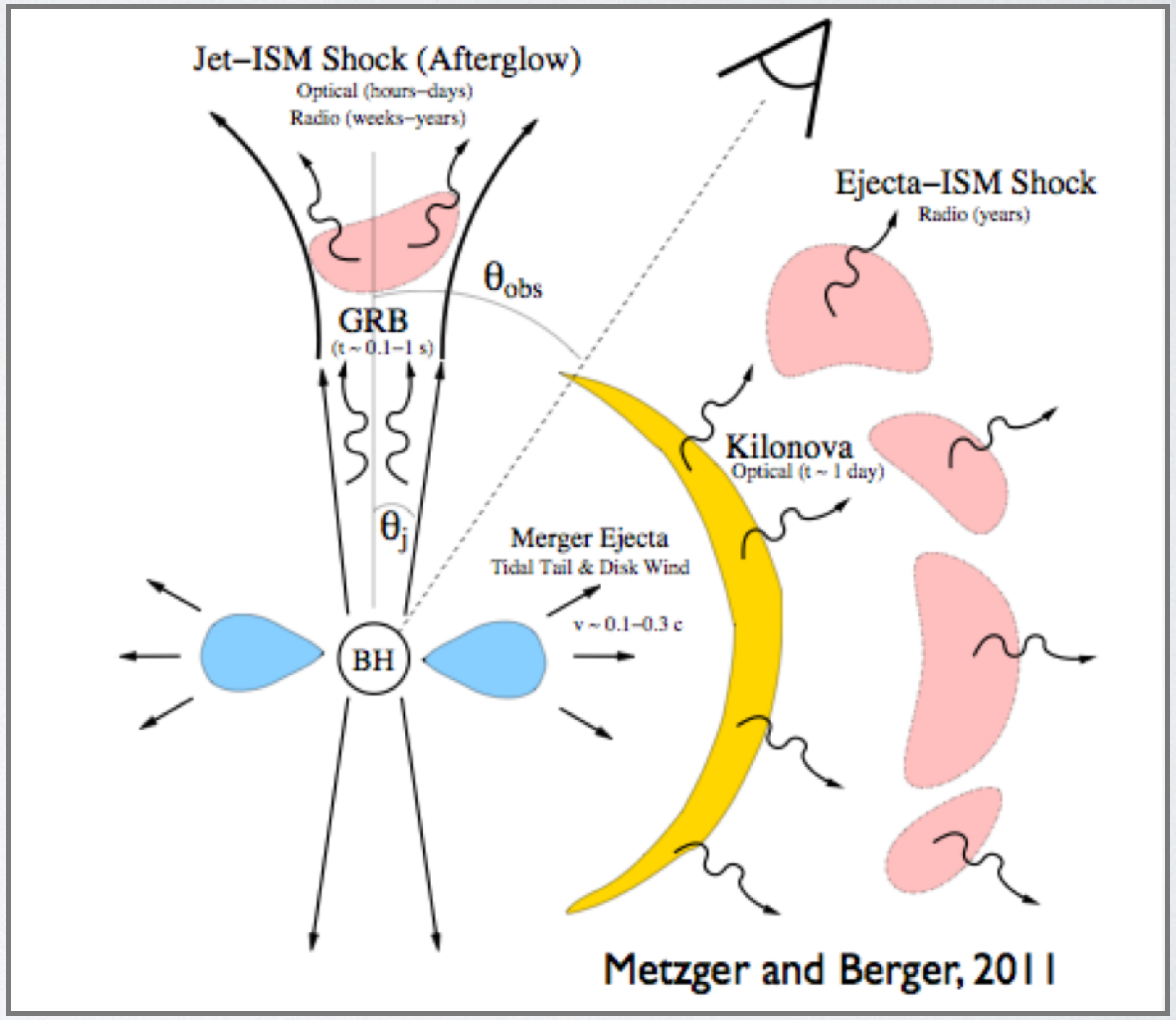
Goldstein et al. 2017, ApJ, 848, L14

GRB 170817A

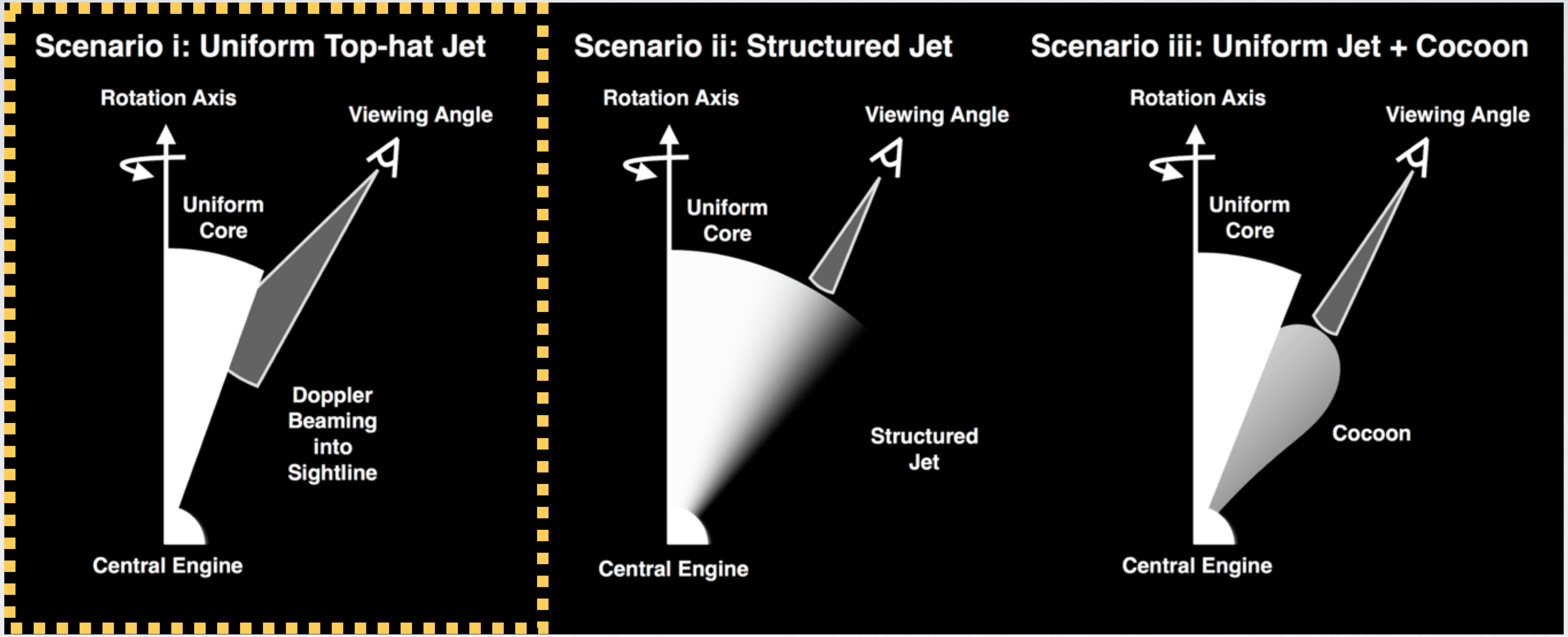




GRB 170817A is the closest GRB ever detected but also the least luminous.



GRB 170817A



We observed outside the jet of a classical sGRB

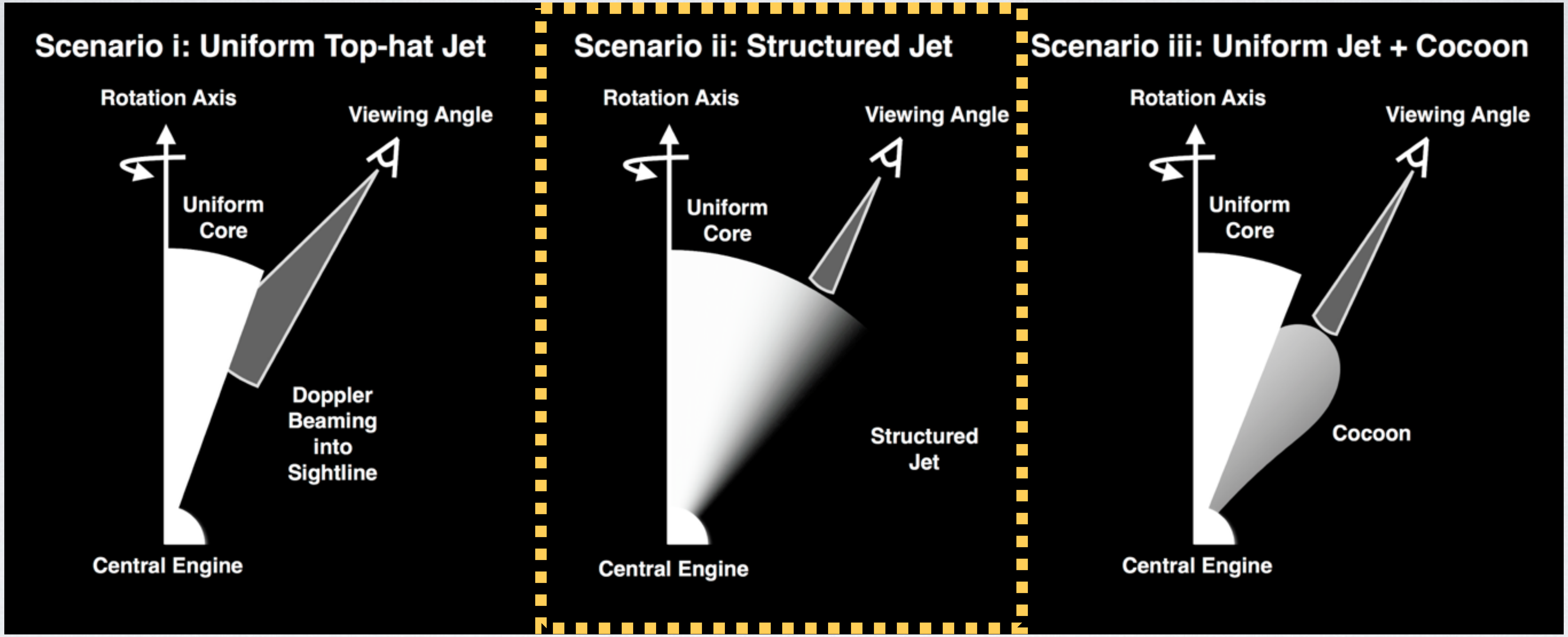
Pros:

- Can naturally explain the lower energetics
- Thermal emission could be from the GRB photosphere or the cocoon

Cons:

- Highly unlikely to observe the jet from the side due to relativistic beaming
- The on-axis Epk would be on the high end of the observed GBM catalog distribution
- Expect bright afterglow in X-ray after ~1 day

GRB 170817A



We observed the less energetic region of a structure jet where the Lorentz factor decreases with viewing angle

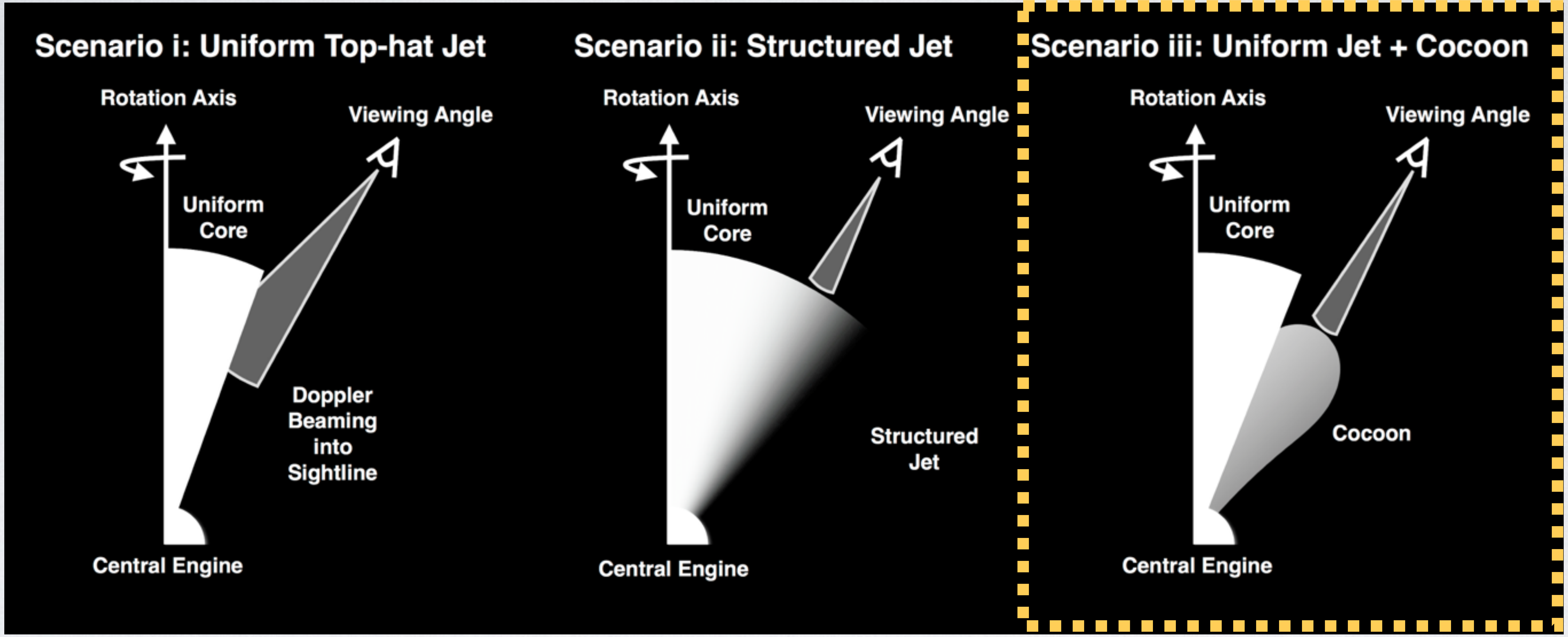
Pros:

- Could produce arbitrary Epk and Eiso values
- GW-EM delay is on the order of T90
- Thermal emission could be from the GRB photosphere or the cocoon

Cons:

- Not entirely clear how such wings are generated or what their Lorentz profiles look like
- On-axis Eiso would still need to be relatively low

GRB 170817A



Hard emission from mildly-relativistic shock breakout and thermal emission from cocoon

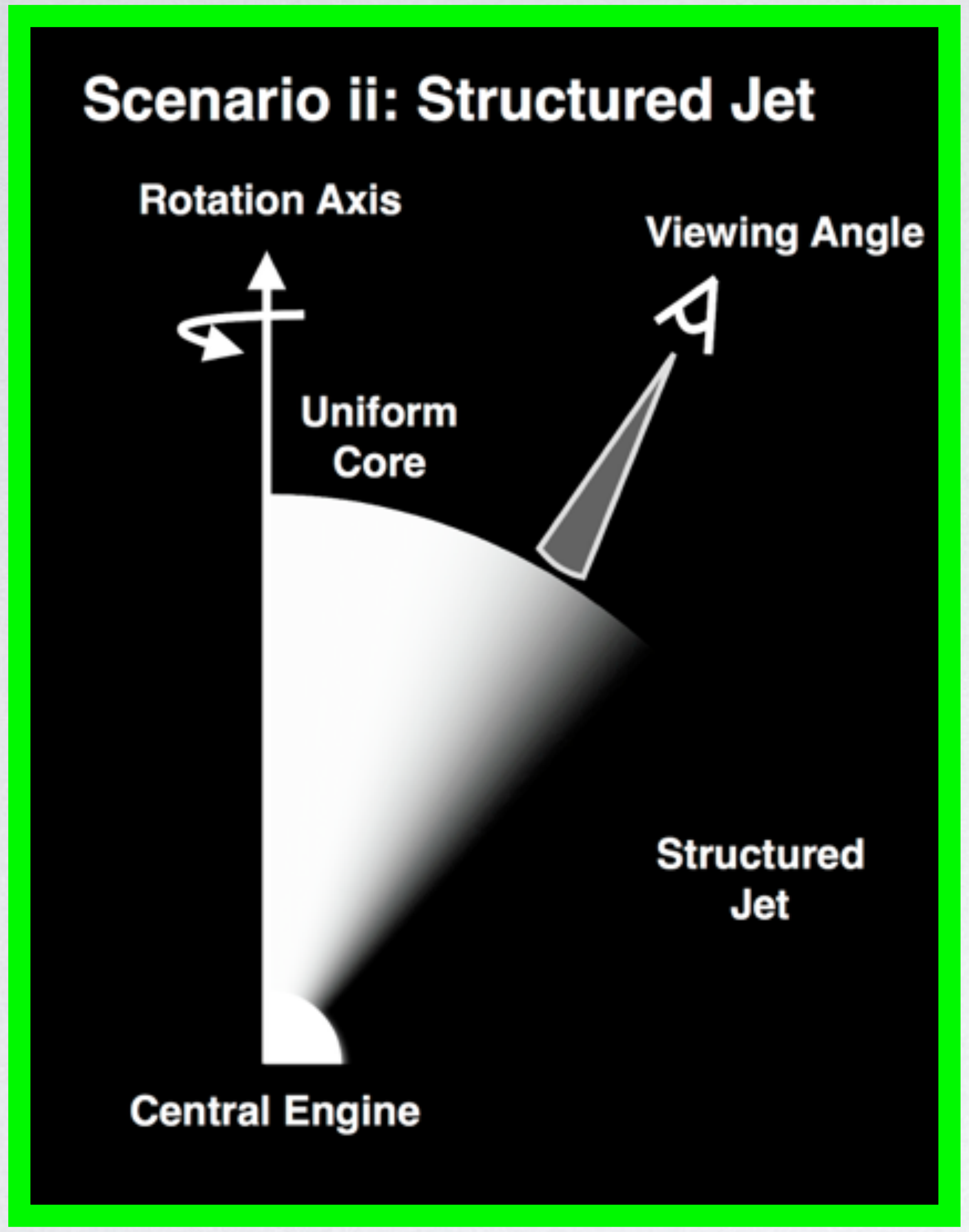
Pros:

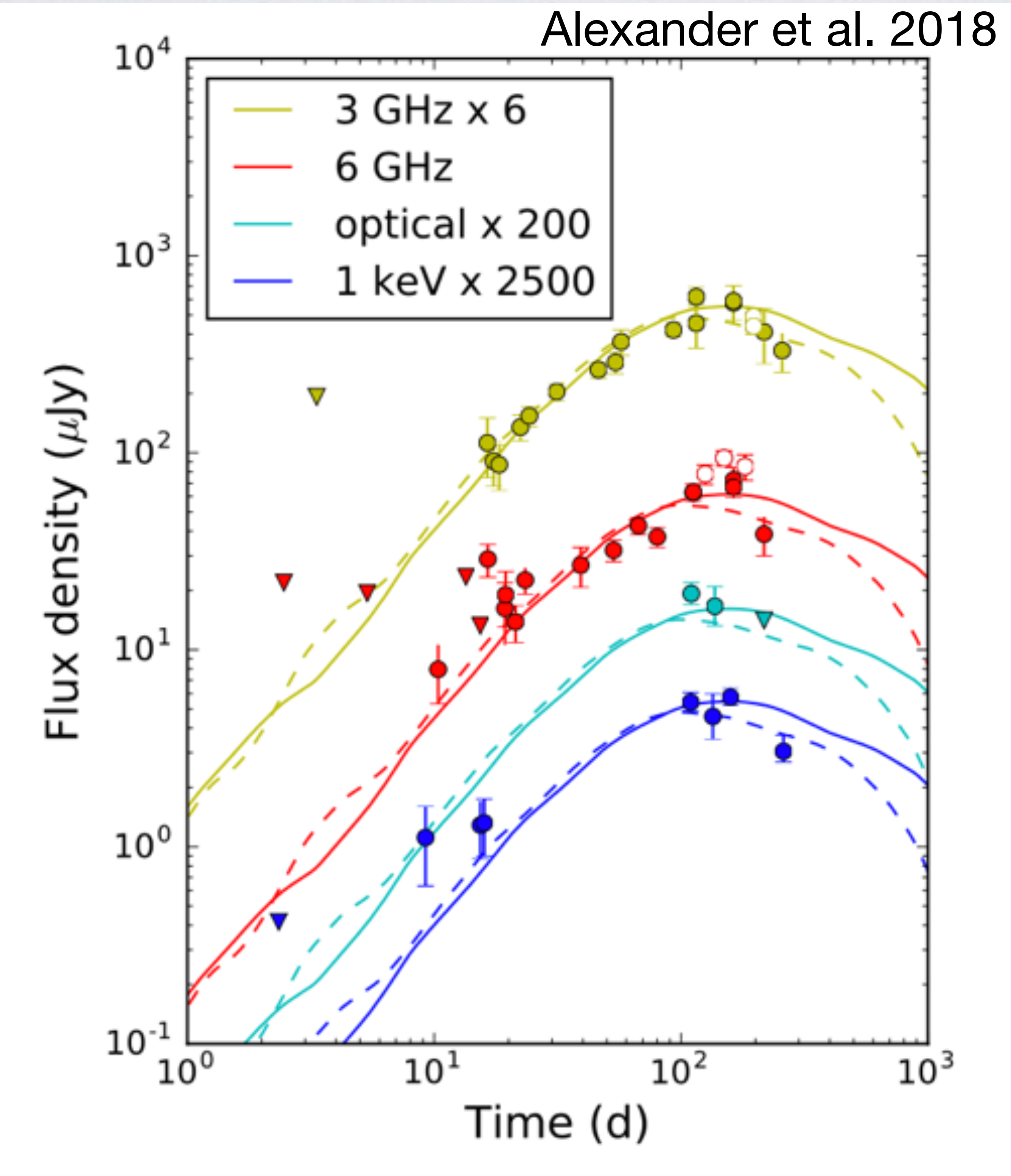
- Can naturally explain the lower energetics
- Could naturally explain both hard and thermal components

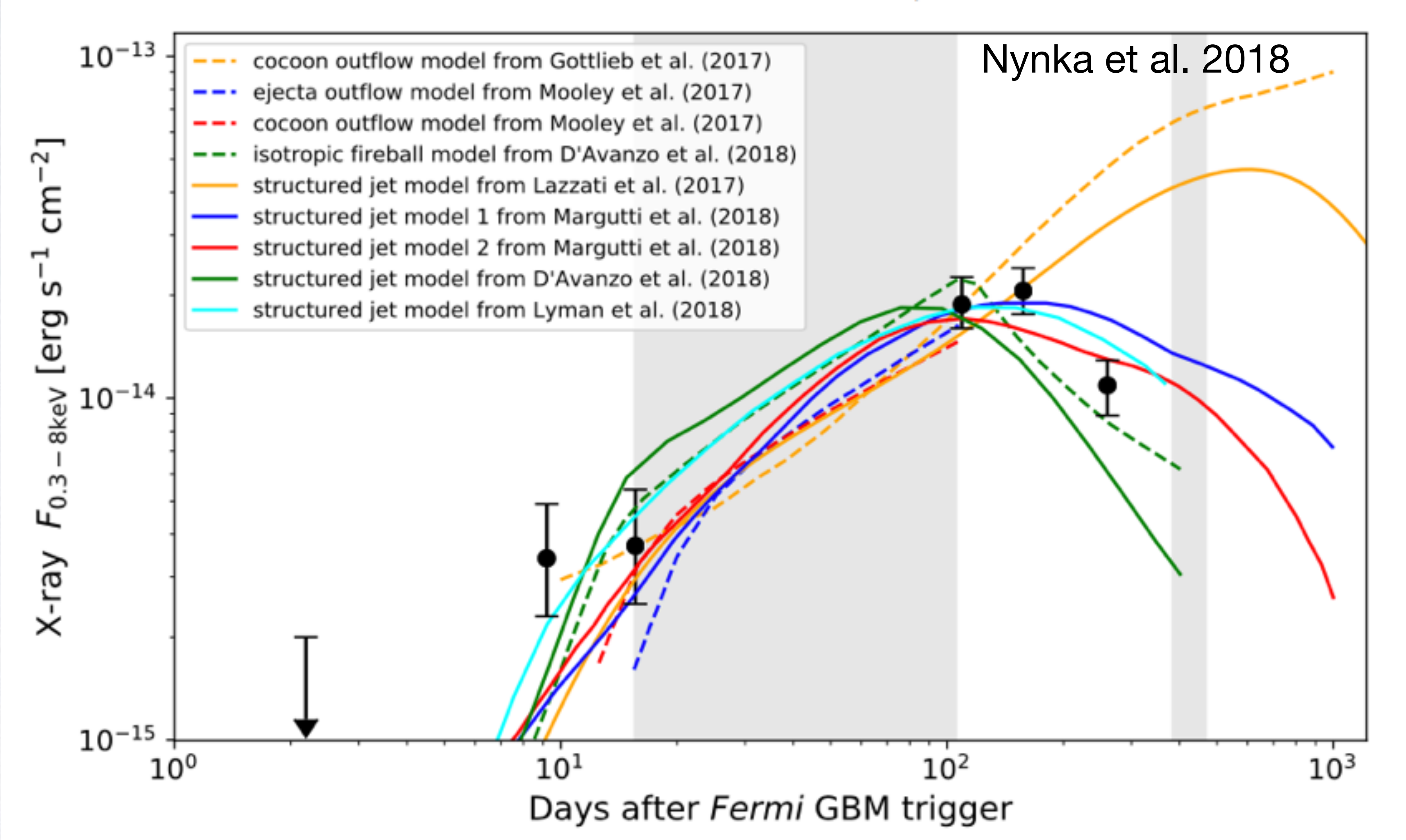
Cons:

- Cannot explain very high Epk values
- Difficult to explain fast variability
- Should overproduce look alike sGRBs

GRB 170817A





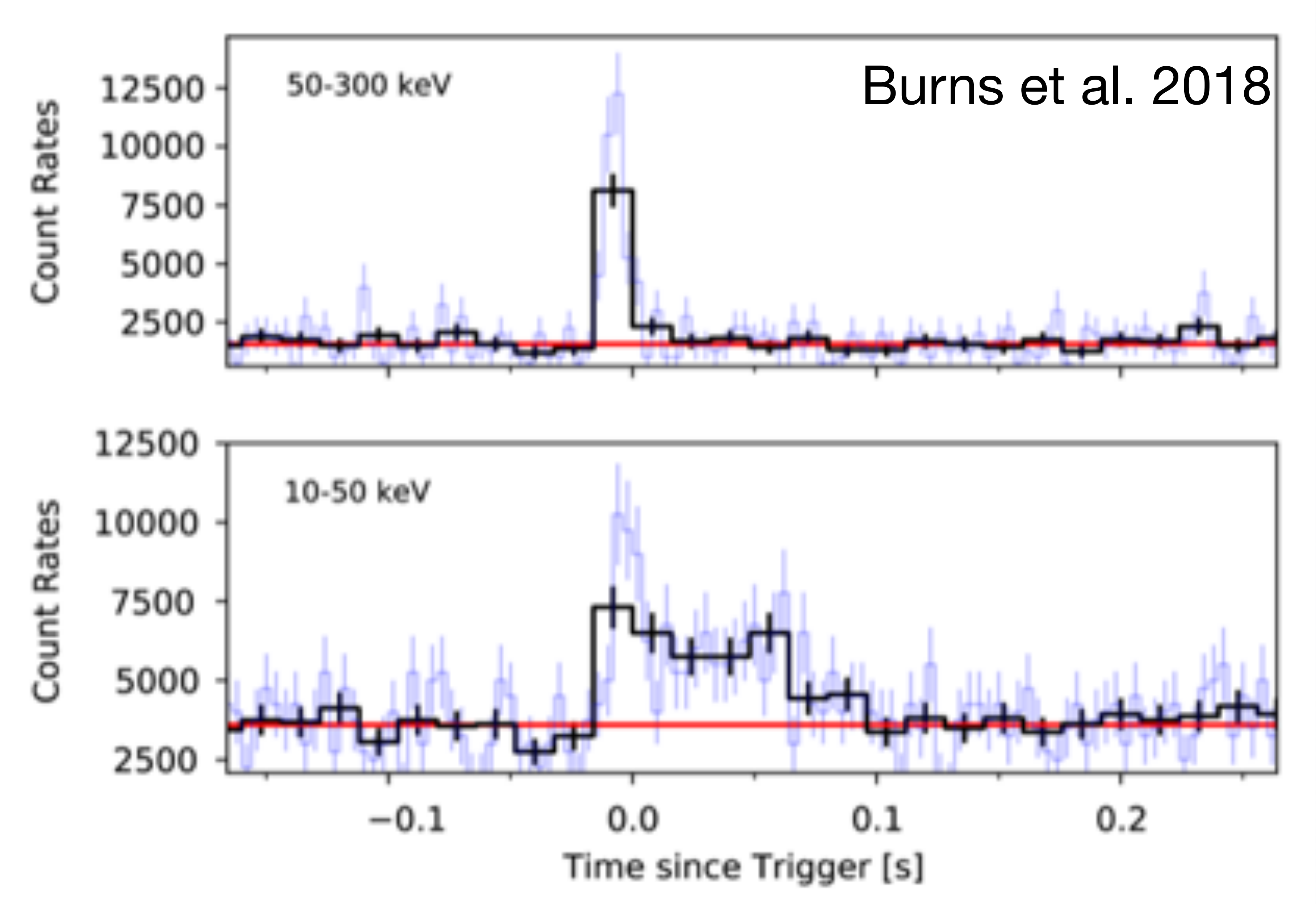


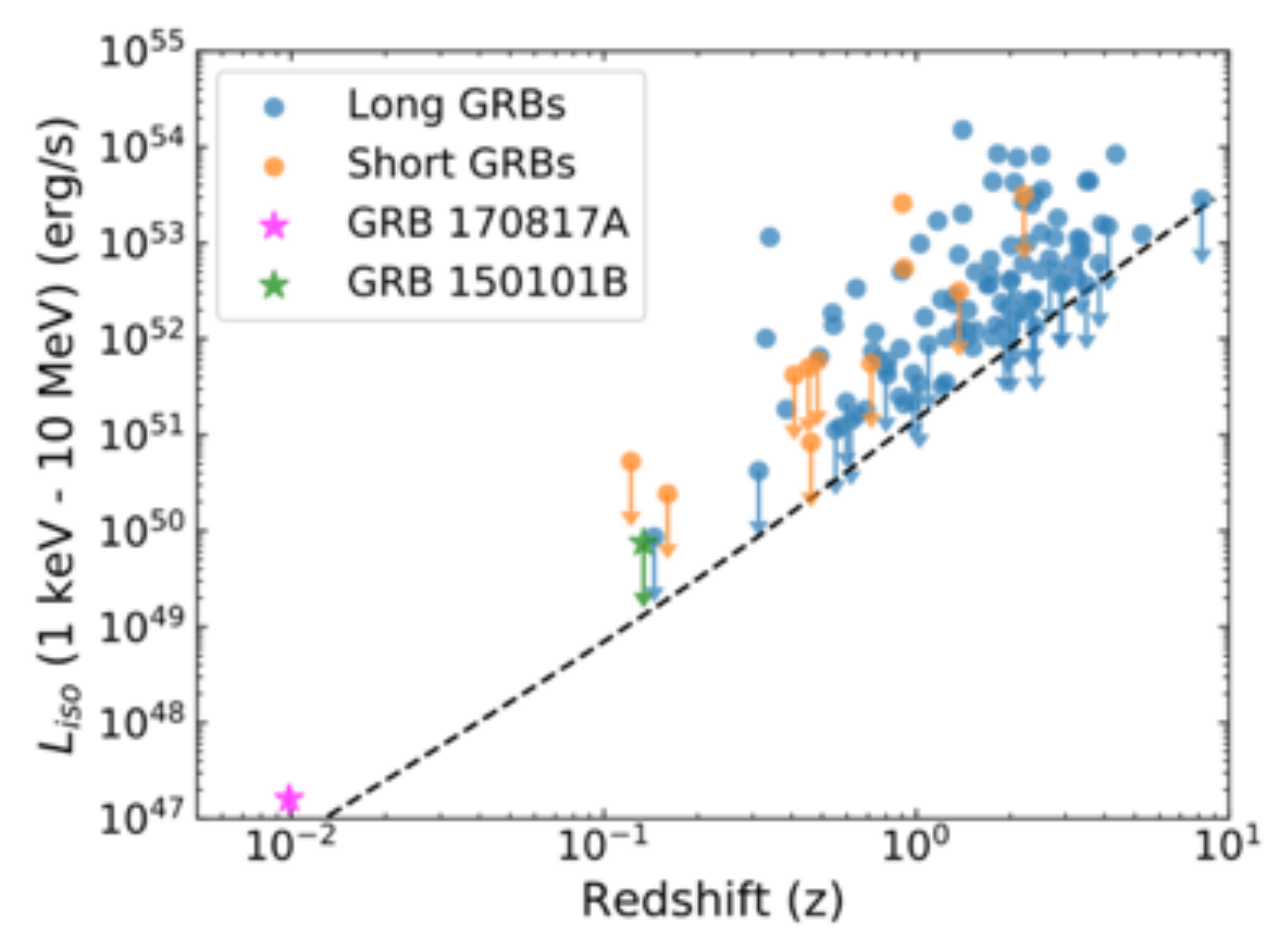
We believe we observed GRB 170817 off-axis

- The off-axis jet is expected to be moving slower and therefore produce weaker gamma-ray emission
- The observed rise and peak of X-ray and radio emission favors the structured jet interpretation

Are there other Gamma-ray Bursts similar to GRB 170817A?

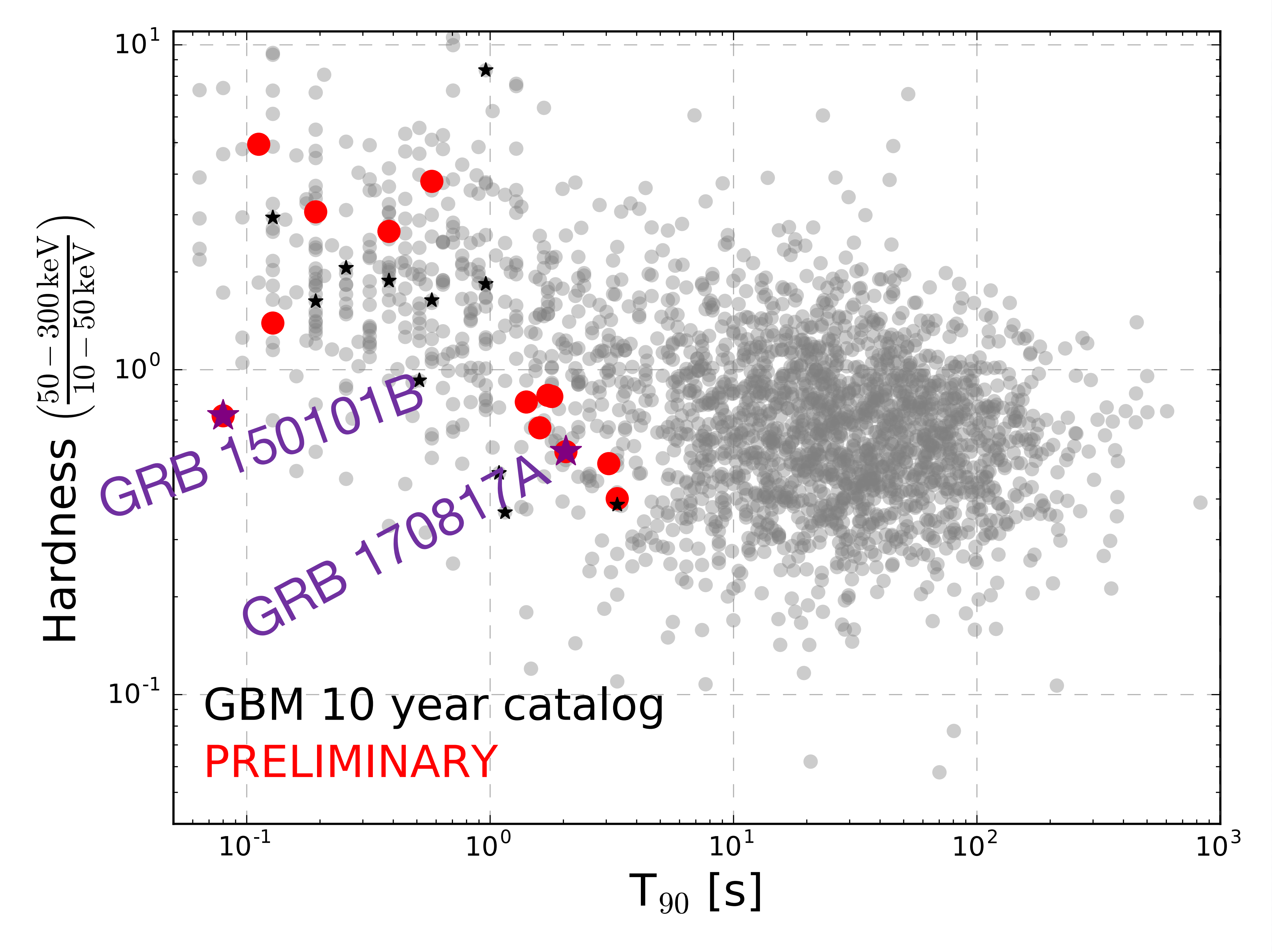
GRB 150101B





- Very hard initial pulse with Epk =1280±590 keV followed by a soft thermal tail with kt~10 keV
- Unlike GRB 170817, 150101B was not under luminous and can be modeled as an on-axis burst
- Suggests that the soft tail is common, but generally undetectable in more distant events
- Thermal tail can be explained as GRB photosphere, but degeneracy with the cocoon model still exists

SIMILAR GRBS IN GBM DATA

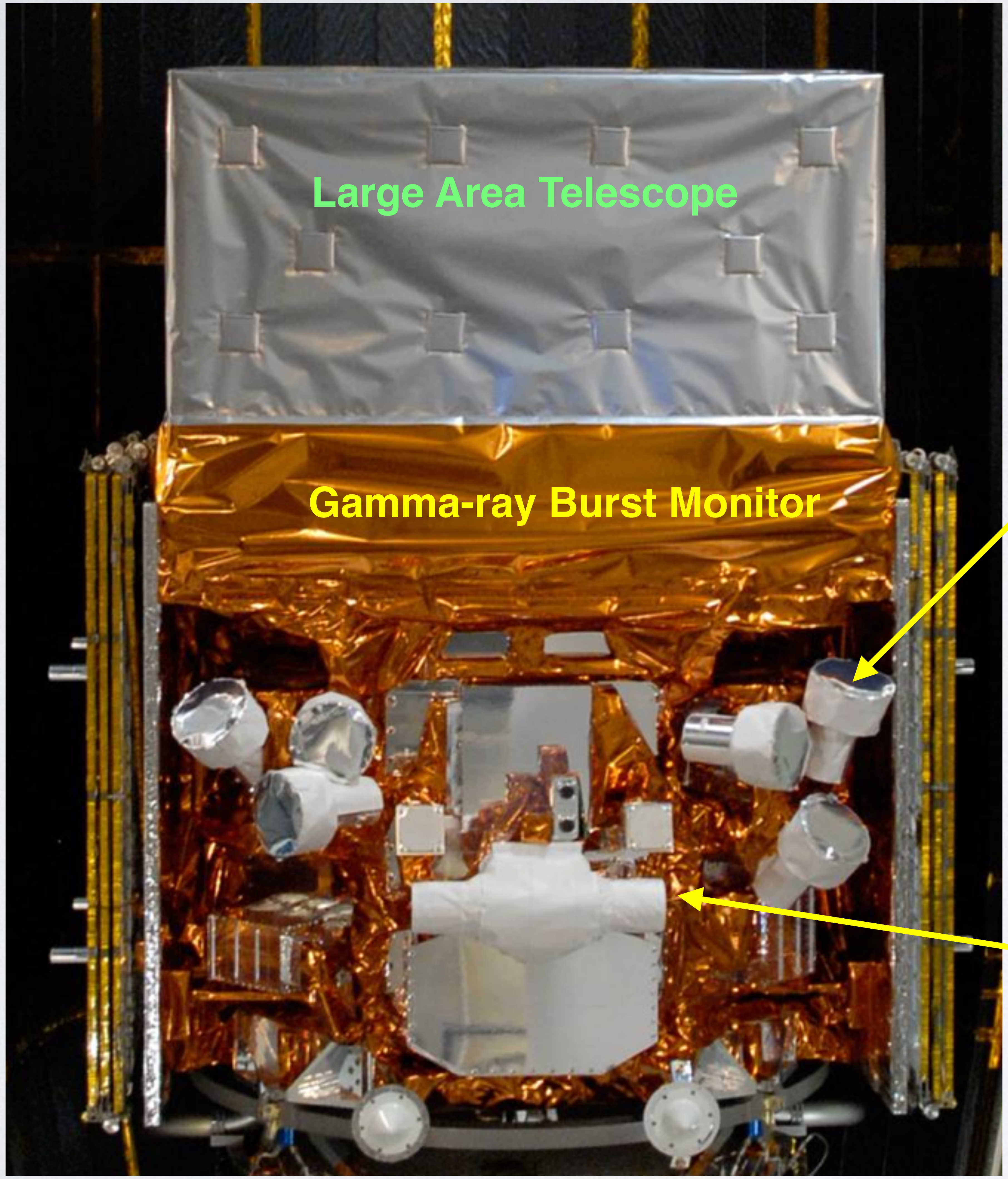


Von Kienlin et al 2019

GRB 170817A-like hard spike followed by a softer thermal tail

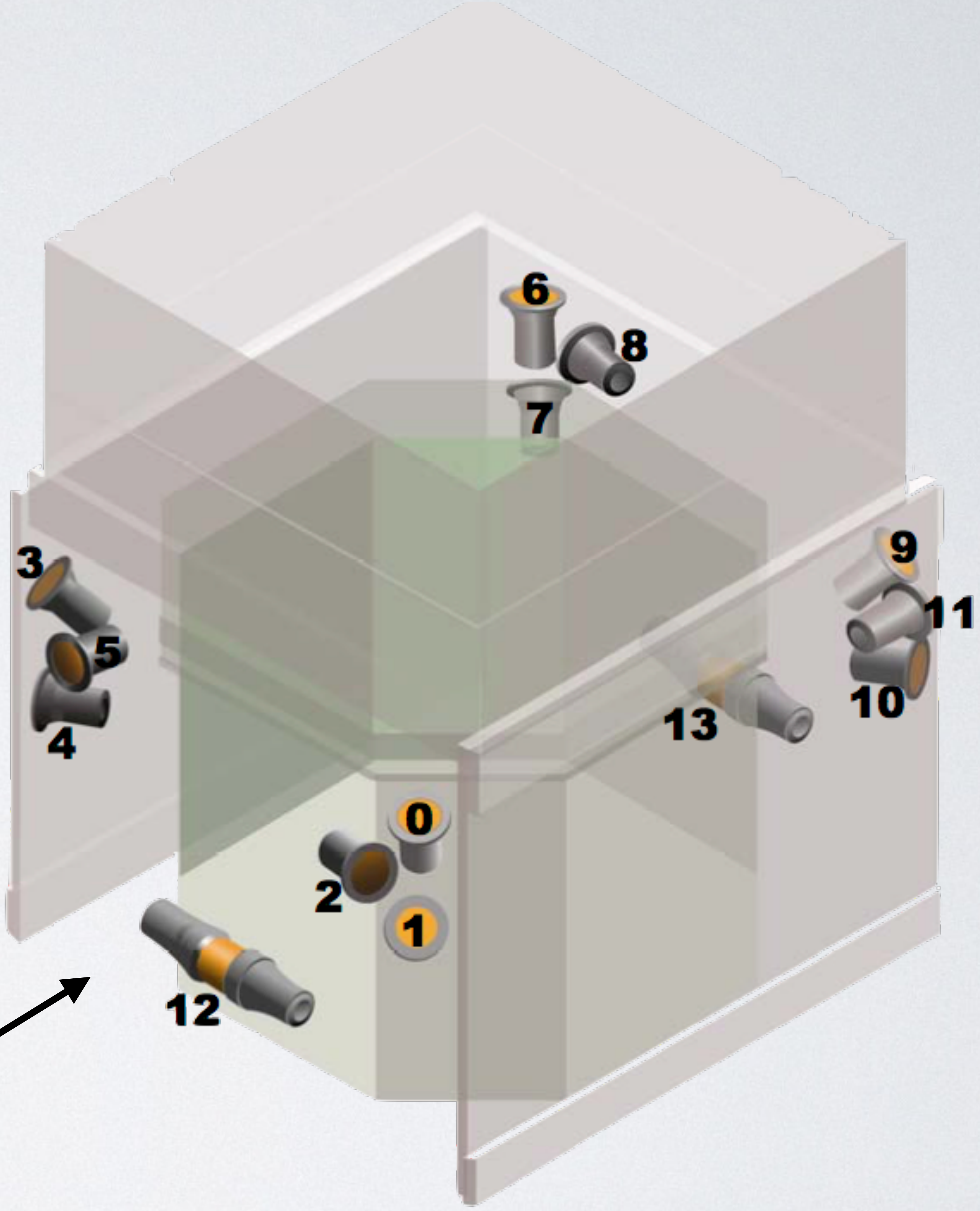
- ~10 similar short GRBs found
- Most likely, all of these SGRBs are relatively nearby
- Longer softer bursts like GRB 170817A may be off-axis
- Shorter harder bursts, like GRB 150101B may be more on-axis
- More coincident SGRB/GW detections are needed to confirm!

FERMI GAMMA-RAY SPACE TELESCOPE



12 NaI detectors
(8keV—1MeV)

2 BGO detectors
(200keV—40MeV)



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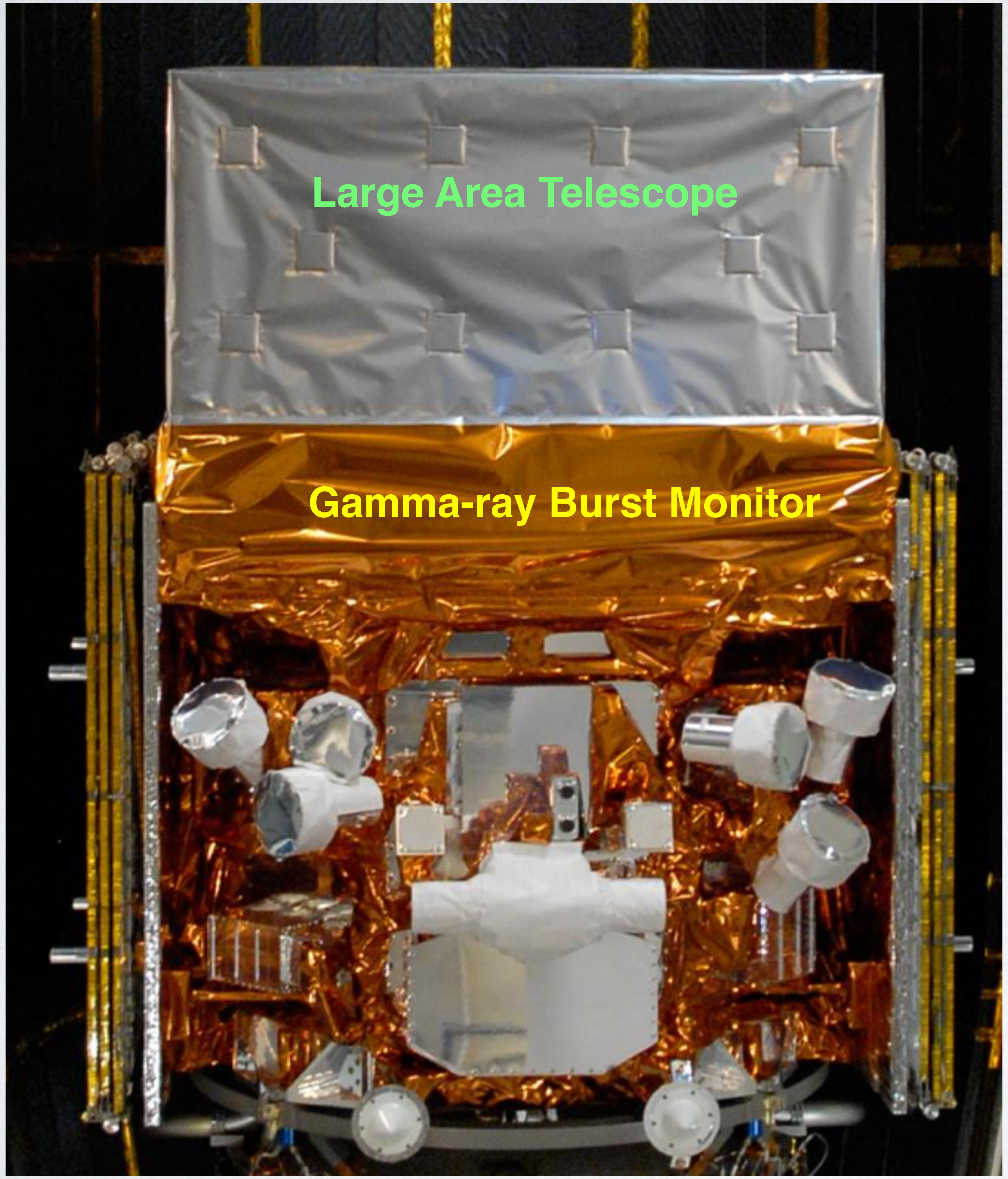

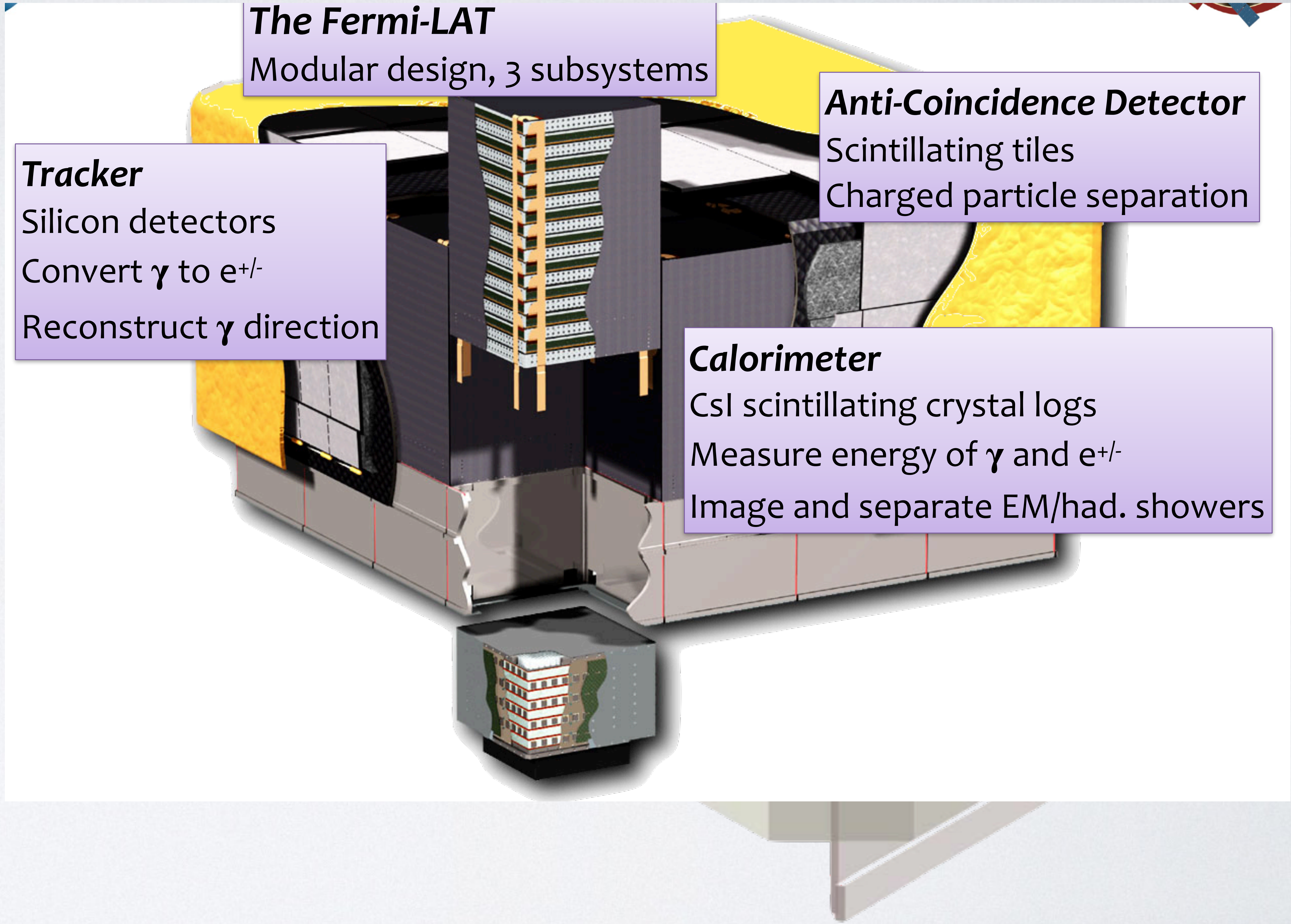

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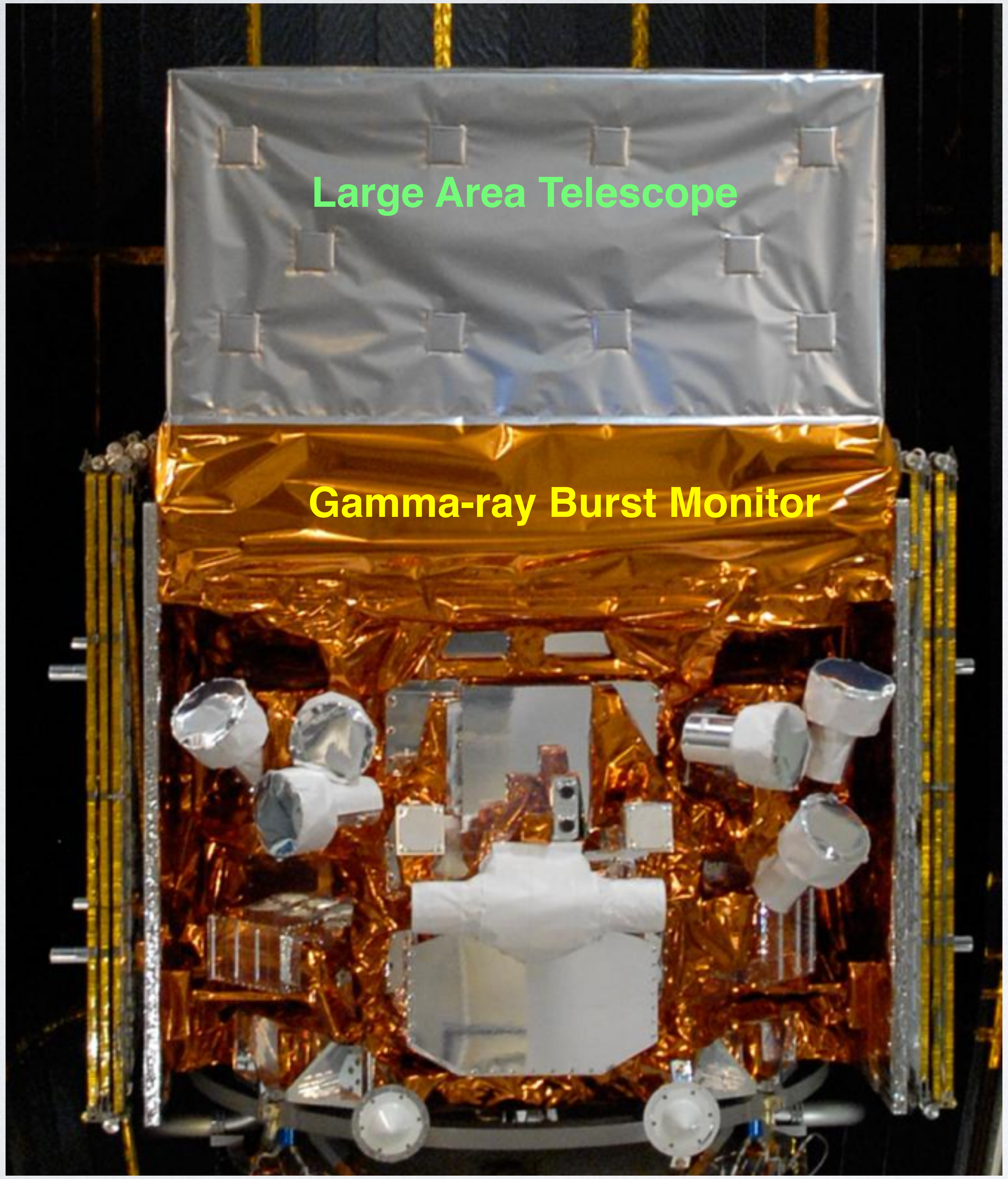
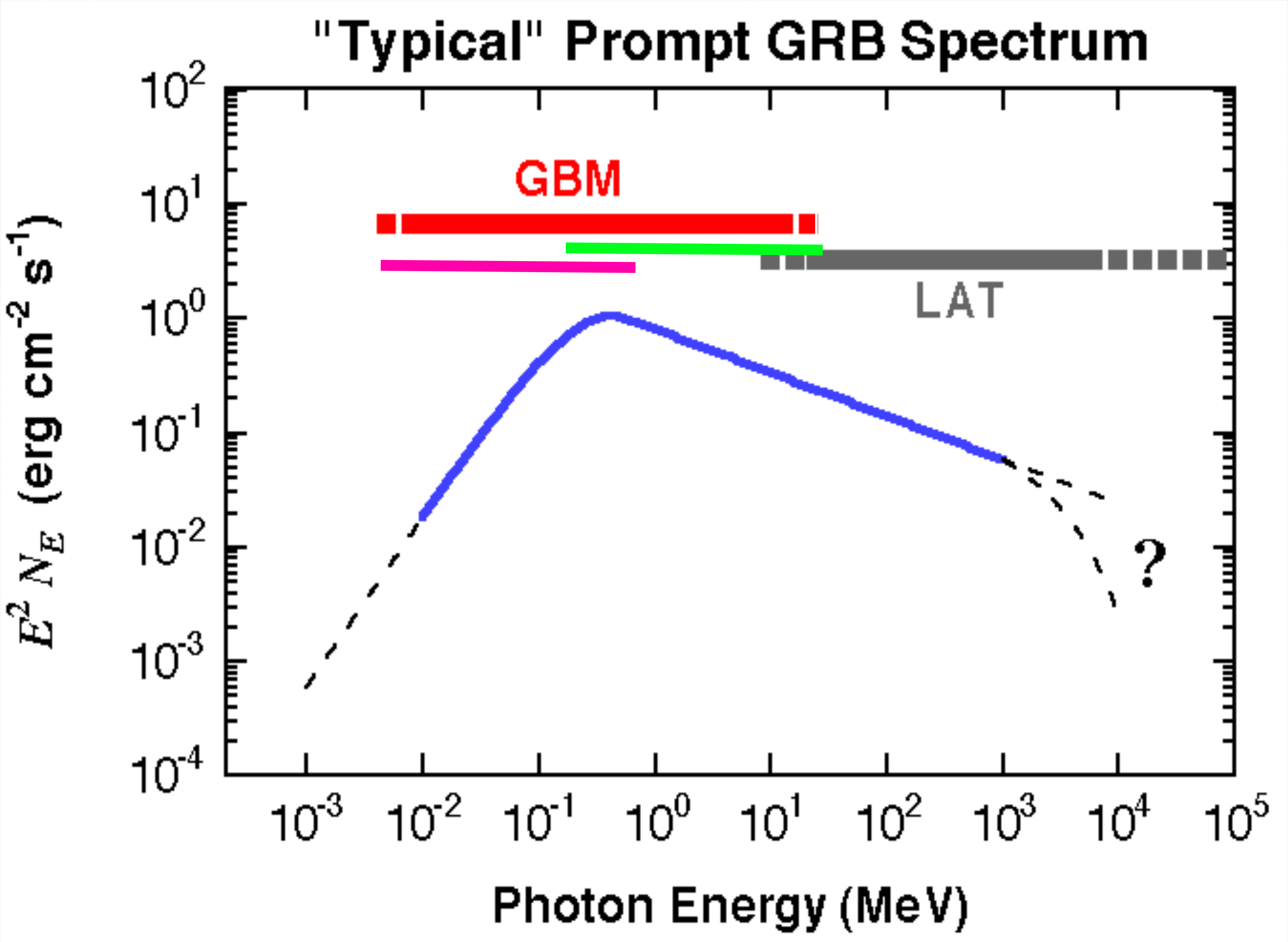
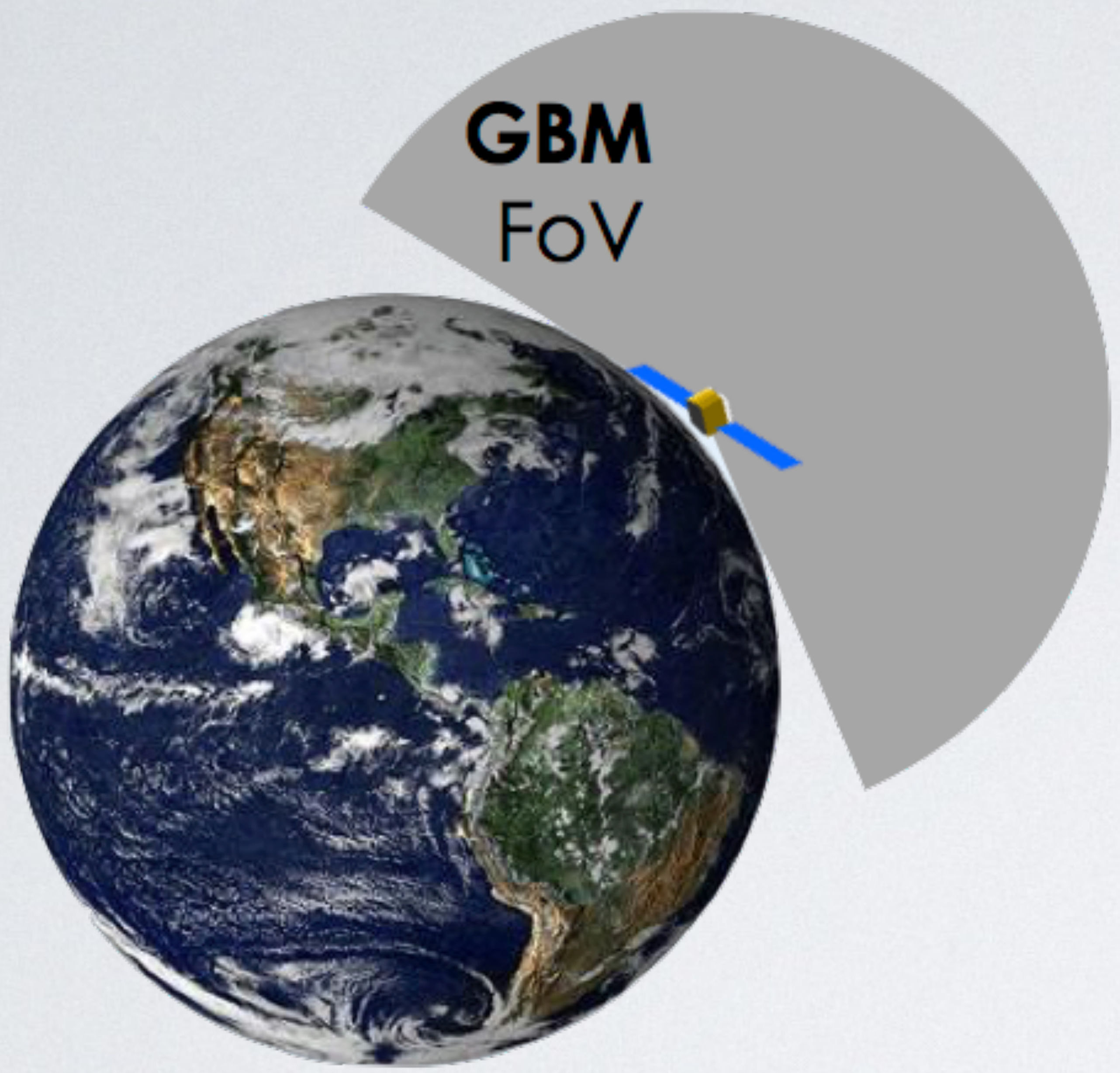


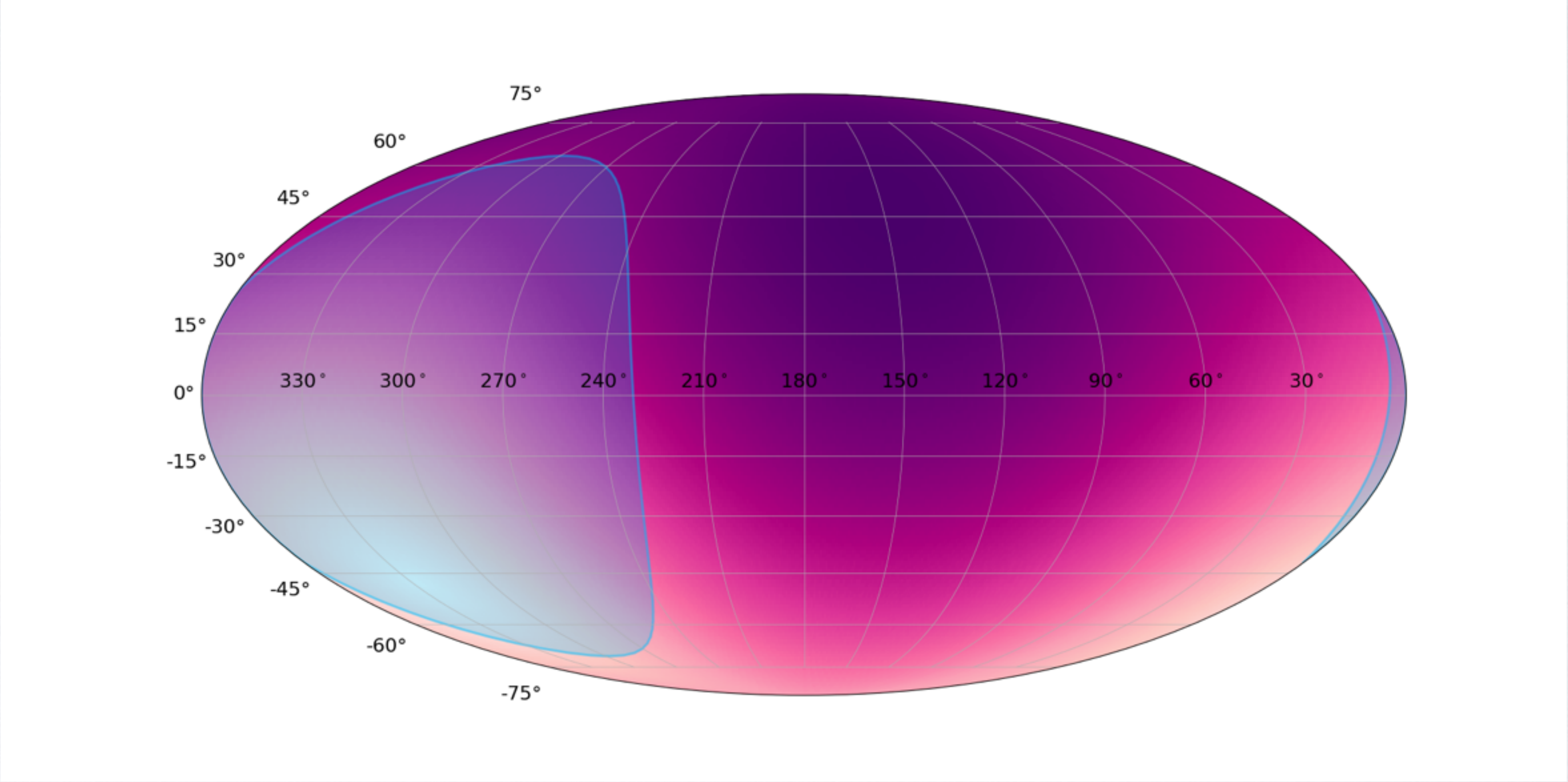


ALL SKY COVERAGE

GBM instantaneous field of view: ~70% of the sky

~87% uptime (off during South Atlantic Anomaly)





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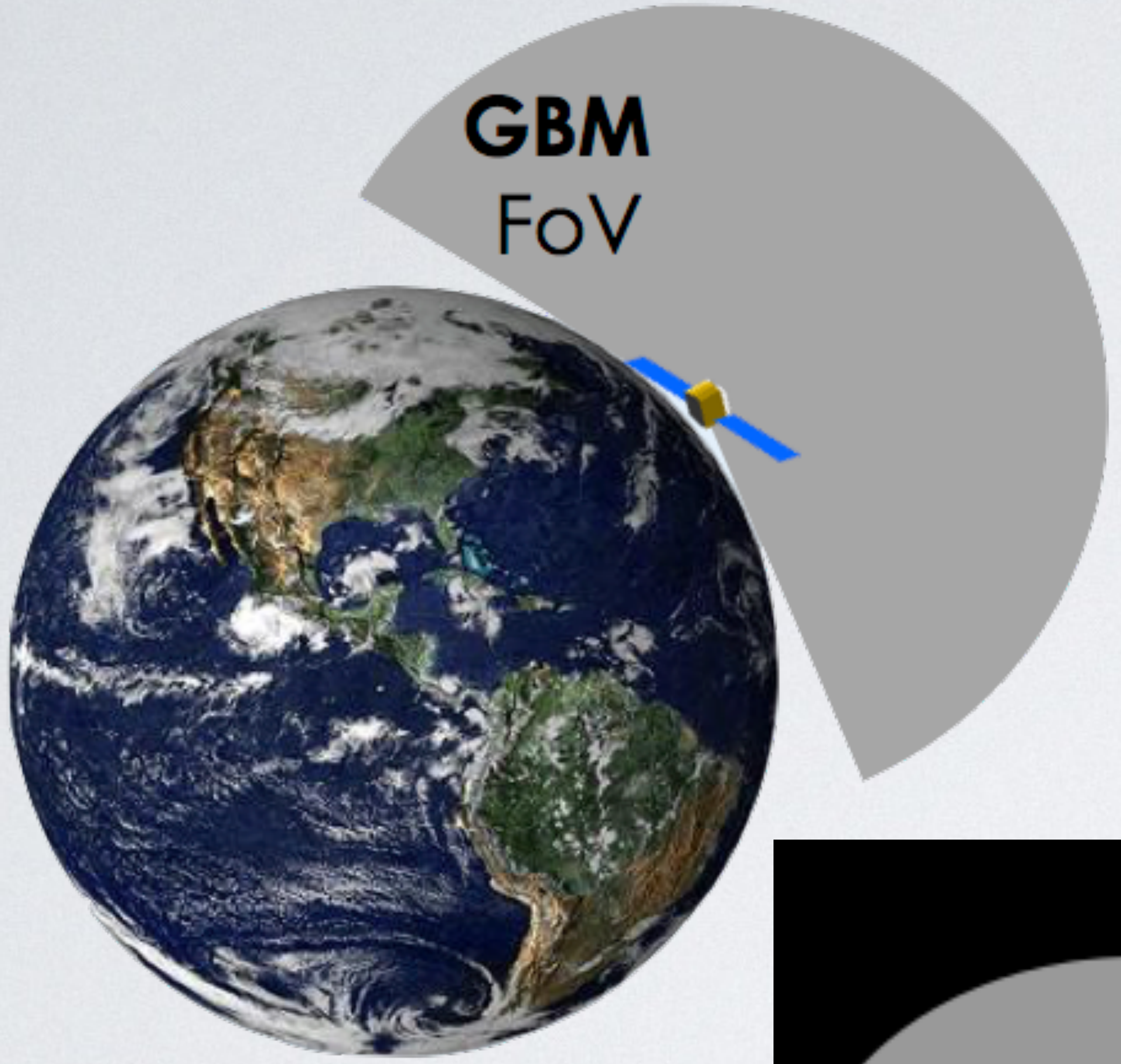
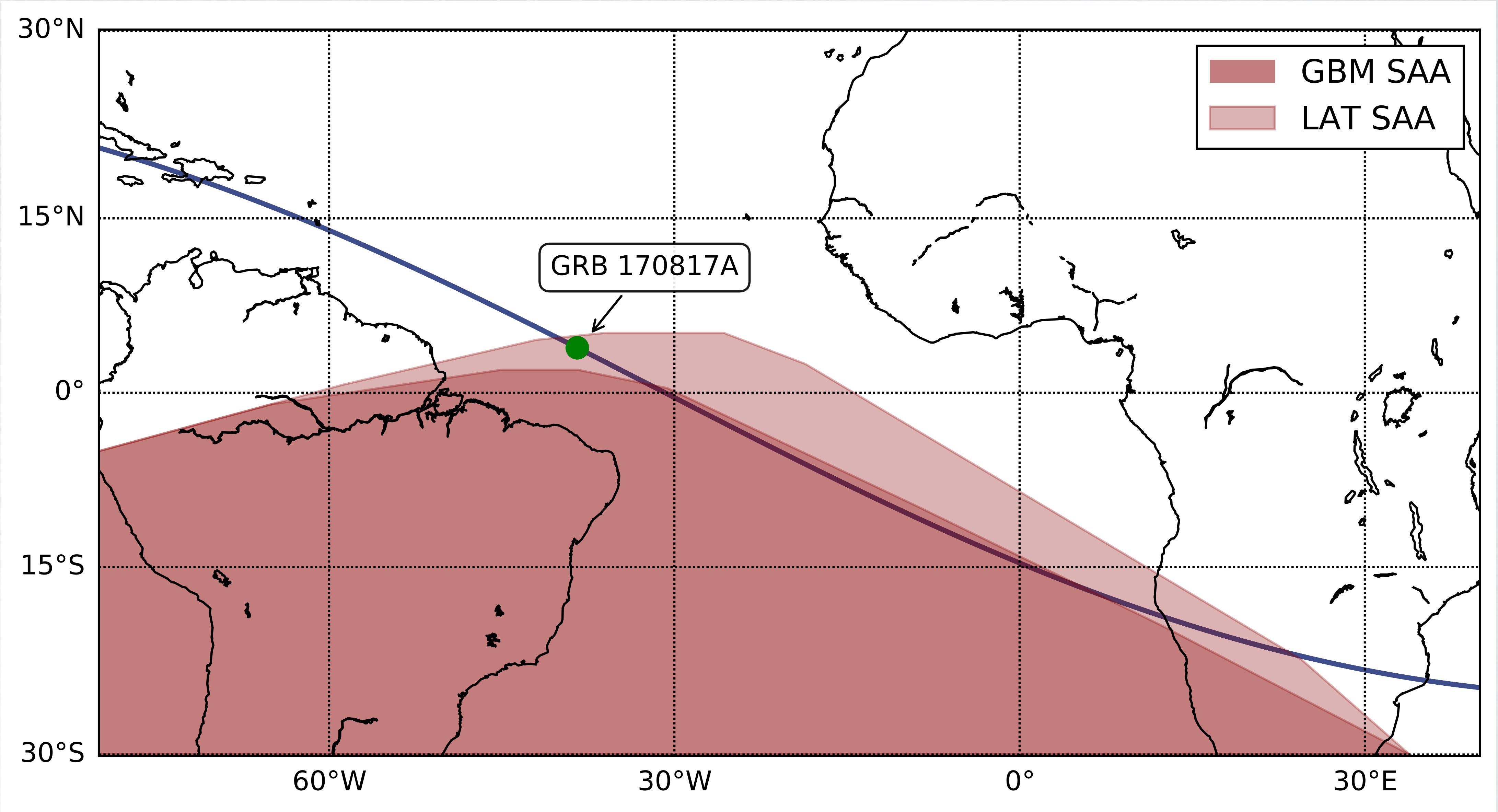
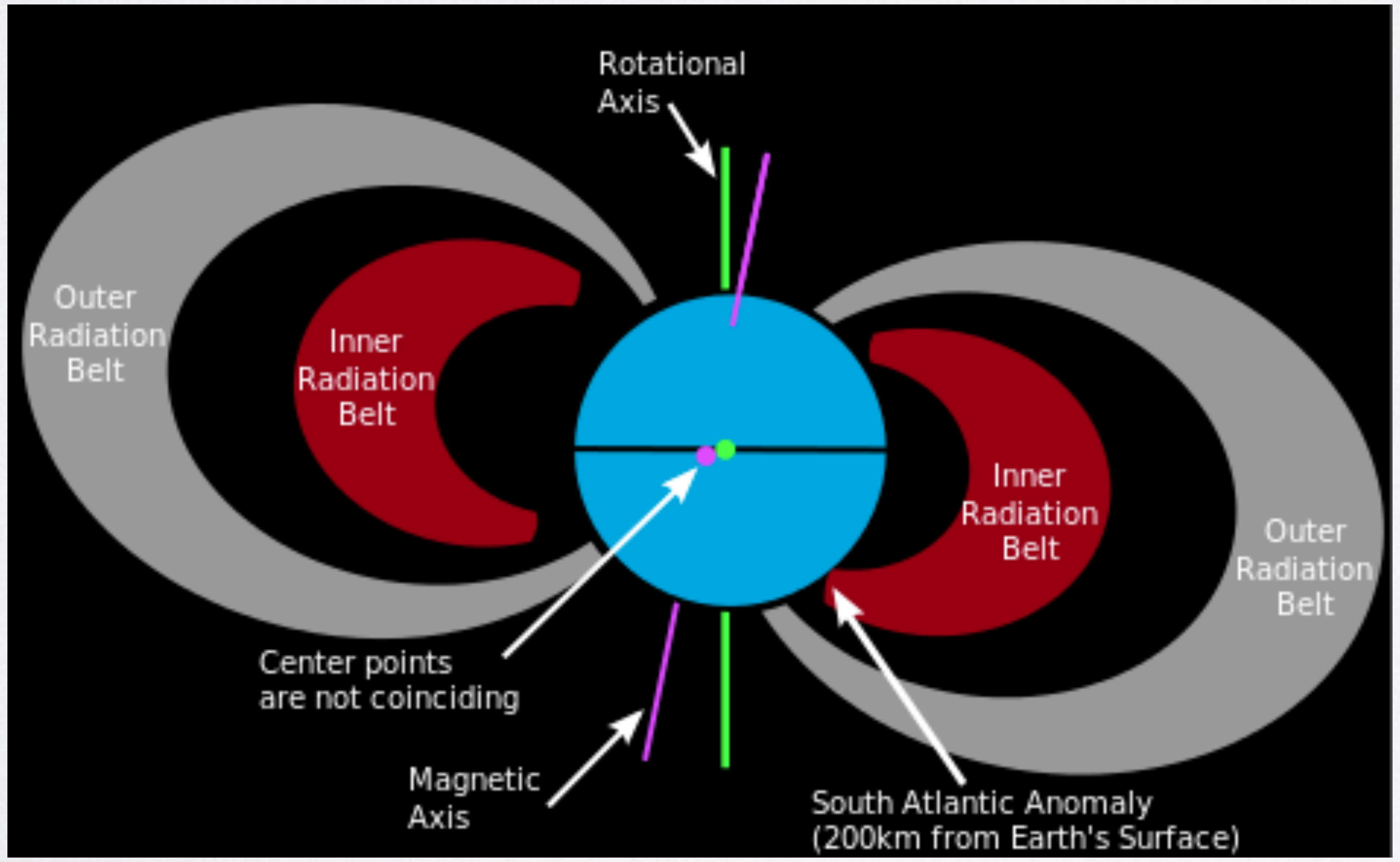
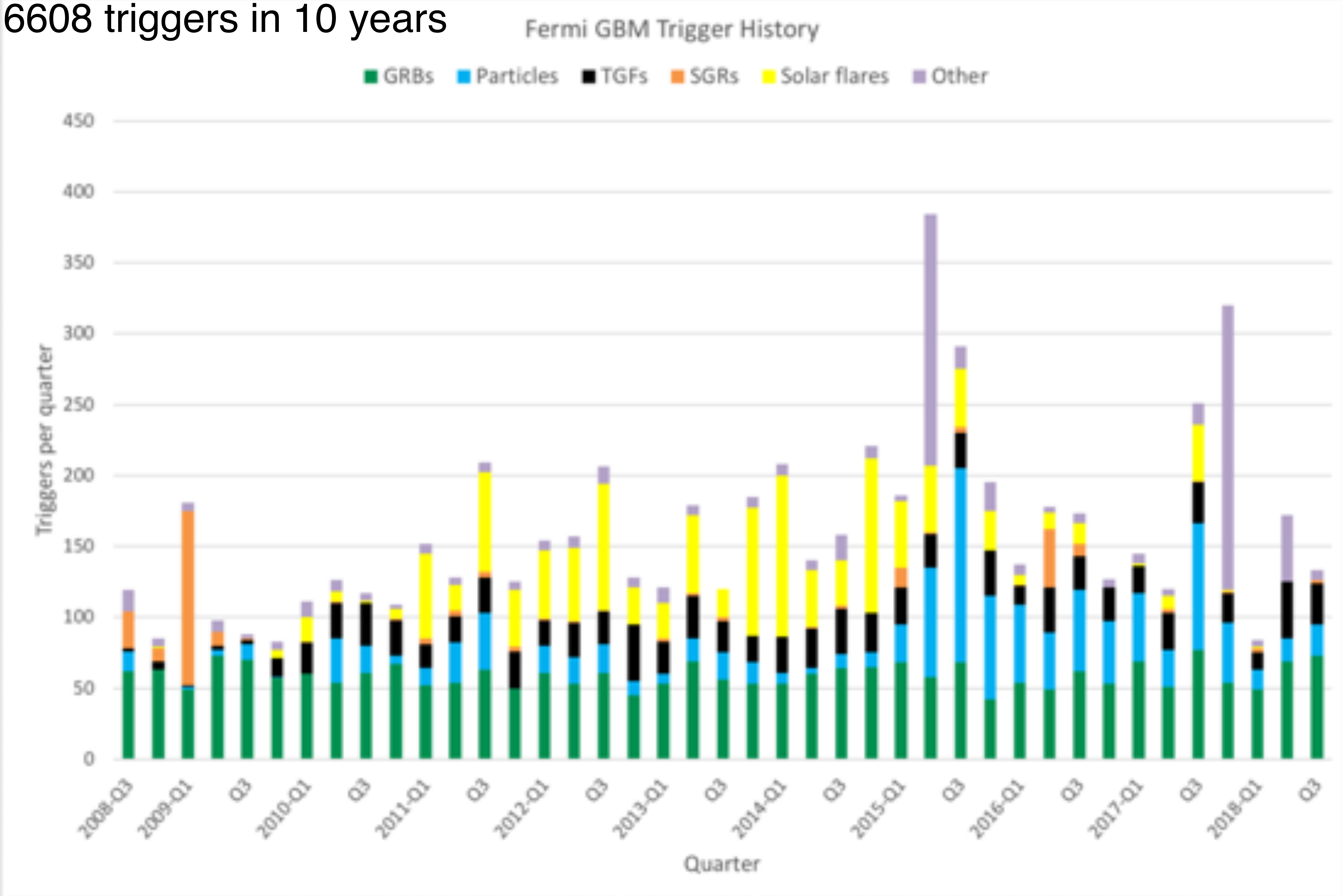




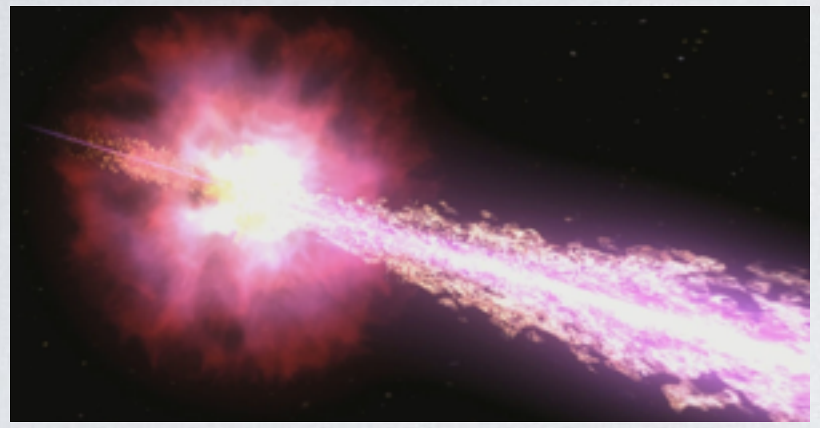


GBM TRIGGERS

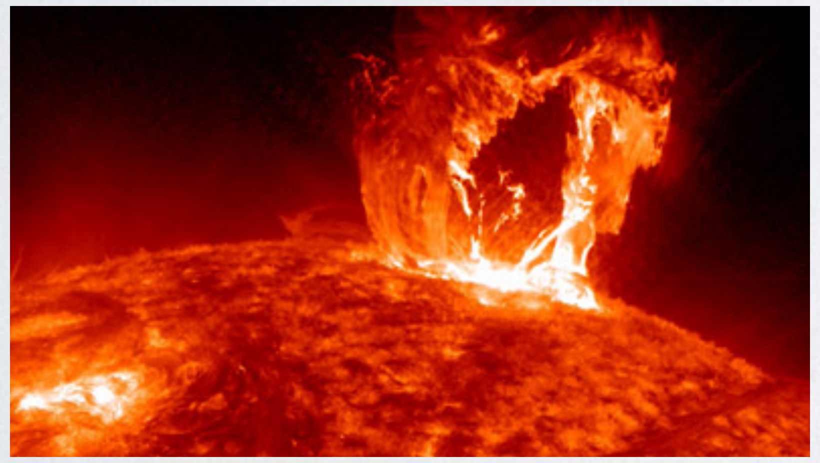
6608 triggers in 10 years



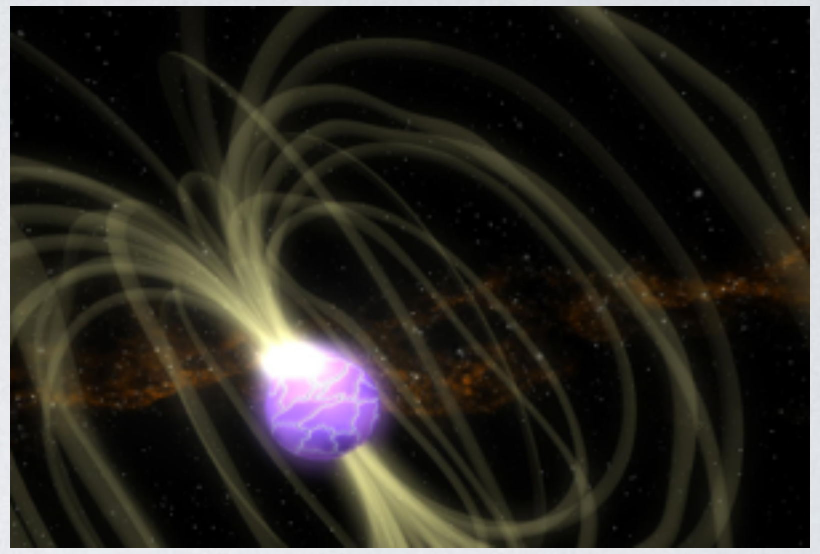
2438 GRBs



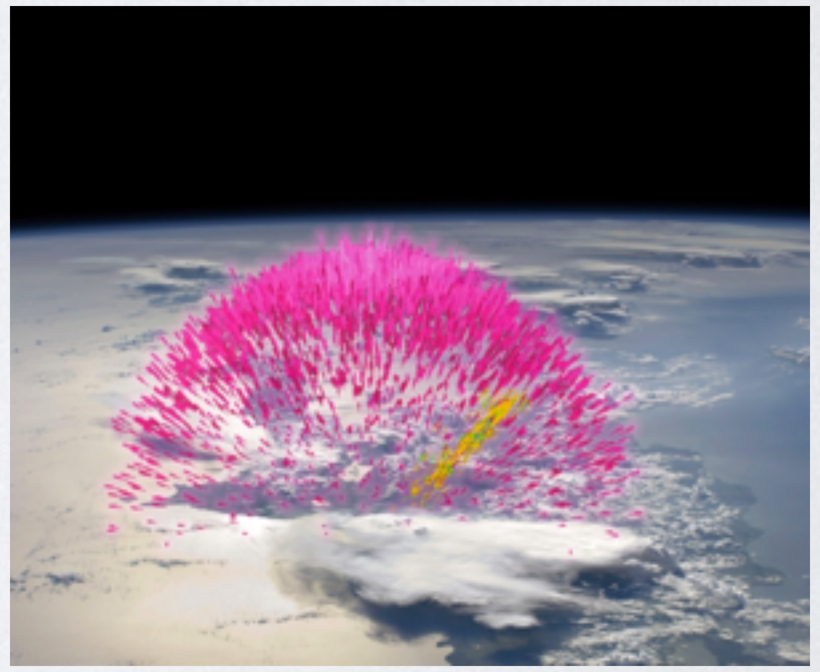
1177 Solar Flares



280 Magnetars



905 TGFs

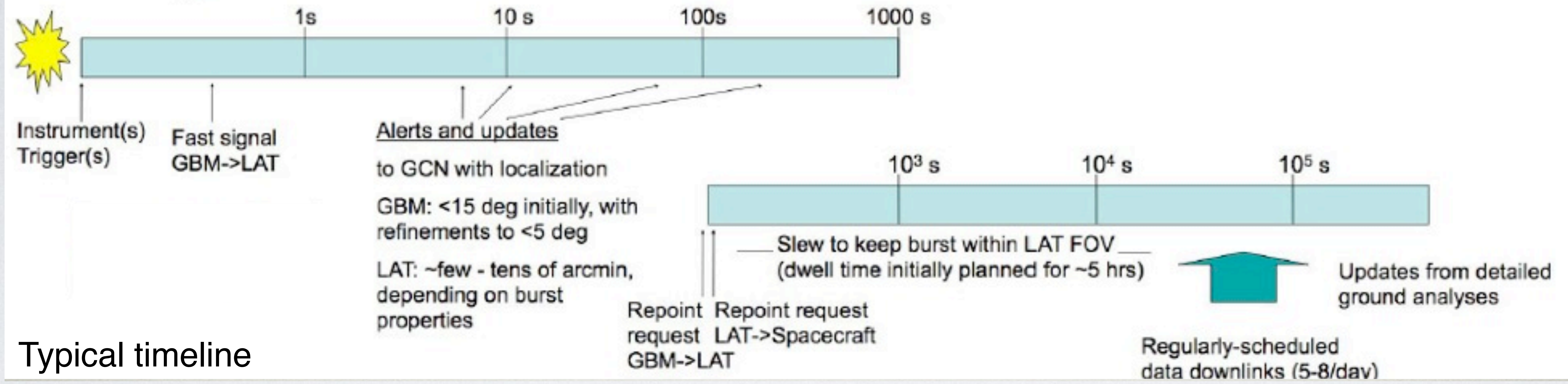


726 Others (pulsars and binaries)

1092 particles

REAL TIME ALERTS

https://fermi.gsfc.nasa.gov/ssc/data/access/gbm/



GCN: The Gamma-ray Coordinates Network

Notices by Fermi-GBM:

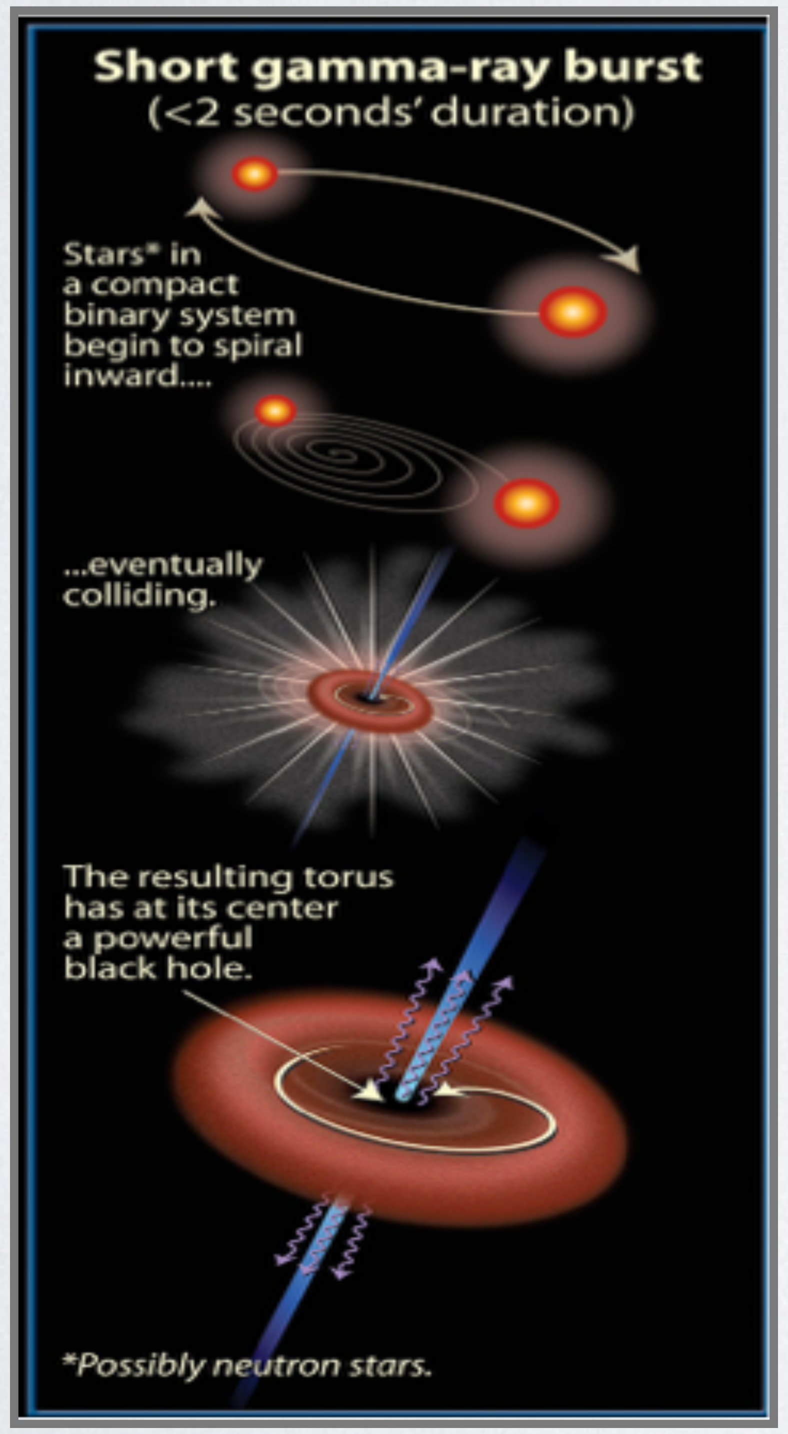
FERMI_GBM_ALERT	~10s	triggered time, lightcurves
FERMI_GBM_FLT_POSITION	~30s	flight location, classification, lightcurves
FERMI_GBM_GND_POSITION	~45s	ground location, lightcurves, map
FERMI_GBM_FINAL_POSITION	minutes — hour	final position, lightcurves, map (healpix)
Circular	few hours	temporal and spectral analyses, or misclassification report

GROUND SEARCH PIPELINES

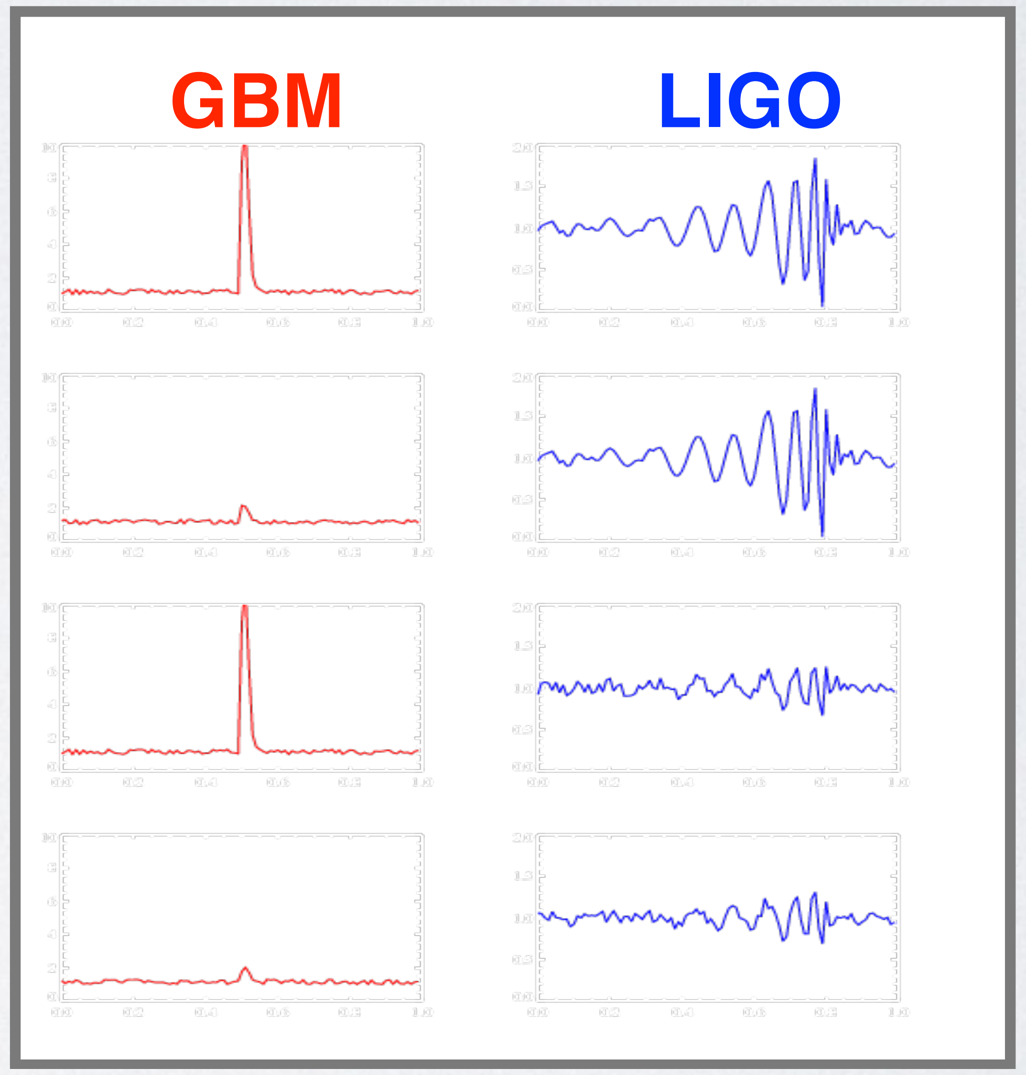
- Continuous Time Tagged Events (CTTE) enabled 2012
  — 2μs, 128 energy channels

1. Untargeted search for subthreshold GRB candidate events

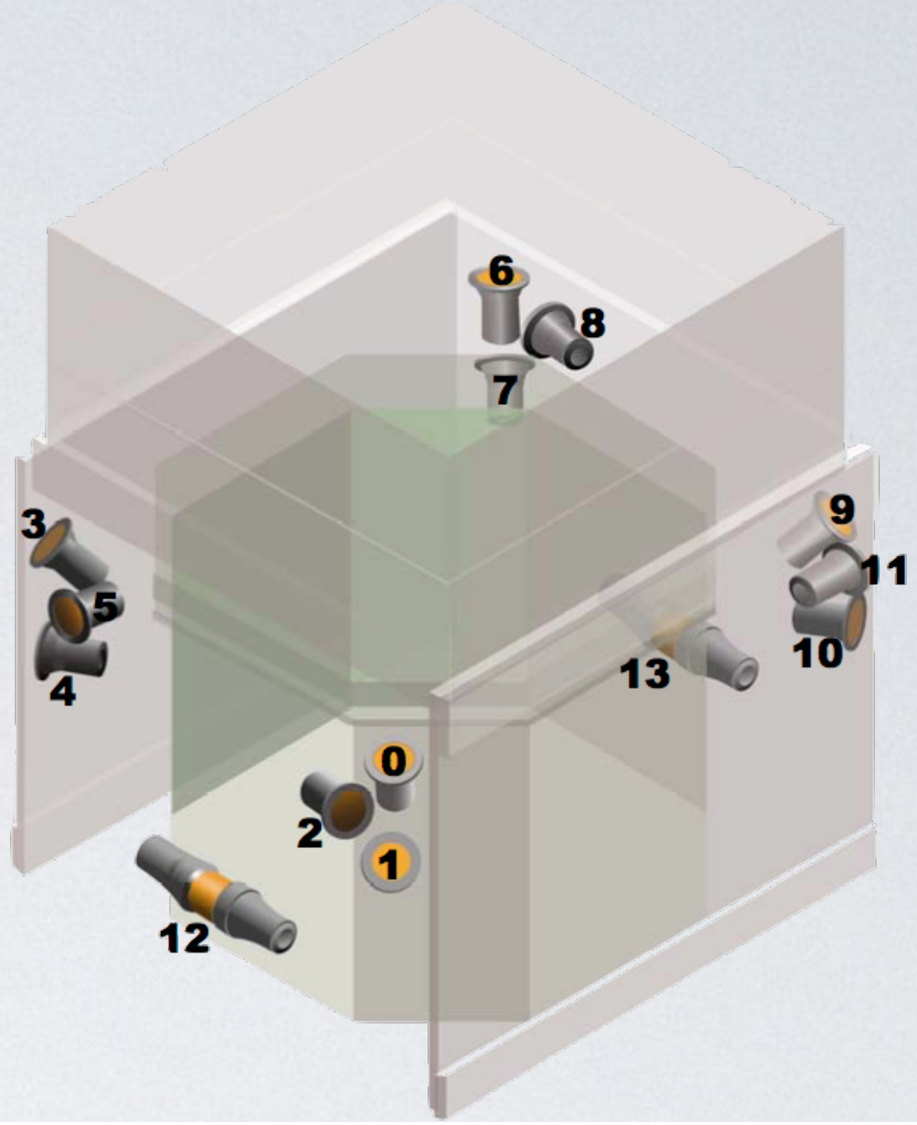
2. Targeted search using input event time and optional skymap



Ideal Scenario	Bright GBM	Bright LIGO
GW150914 Scenario	Sub-threshold GBM	Bright LIGO
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO



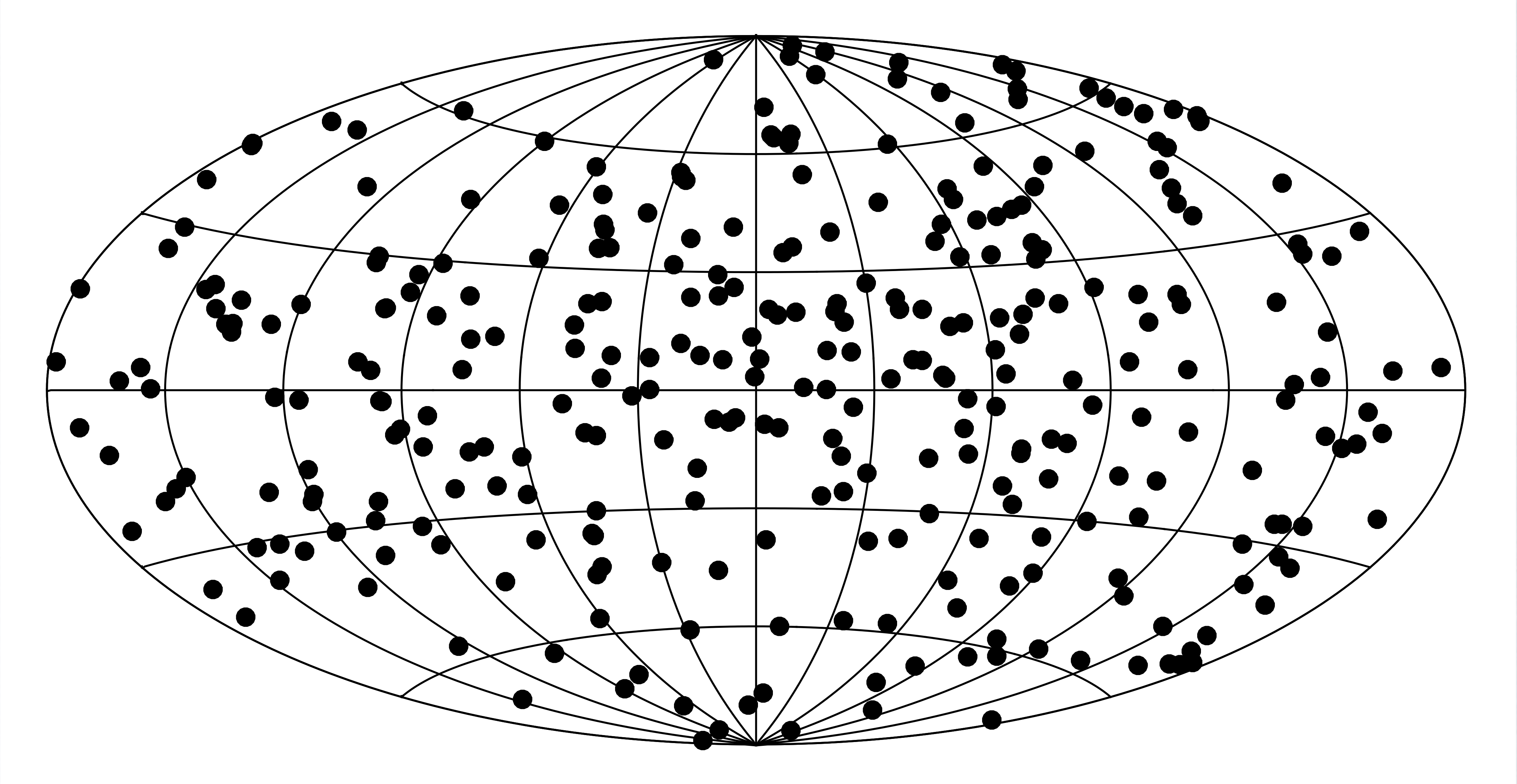
UNTARGETED SEARCH



Extends the onboard trigger algorithms, with improved background model.

- Looks for signals in 2 NaI detectors with 2.5σ and 1.25σ excess above background.
- The 2 signal detectors must have valid geometry for a point source.
- **18 timescales: 64ms to 32s**.
  - Only candidates <2.8s are reported at the moment.
- **4 energy ranges** optimized for short GRBs.
  - 27—539 keV; 50—539 keV; 102—539 keV; 102—985 keV

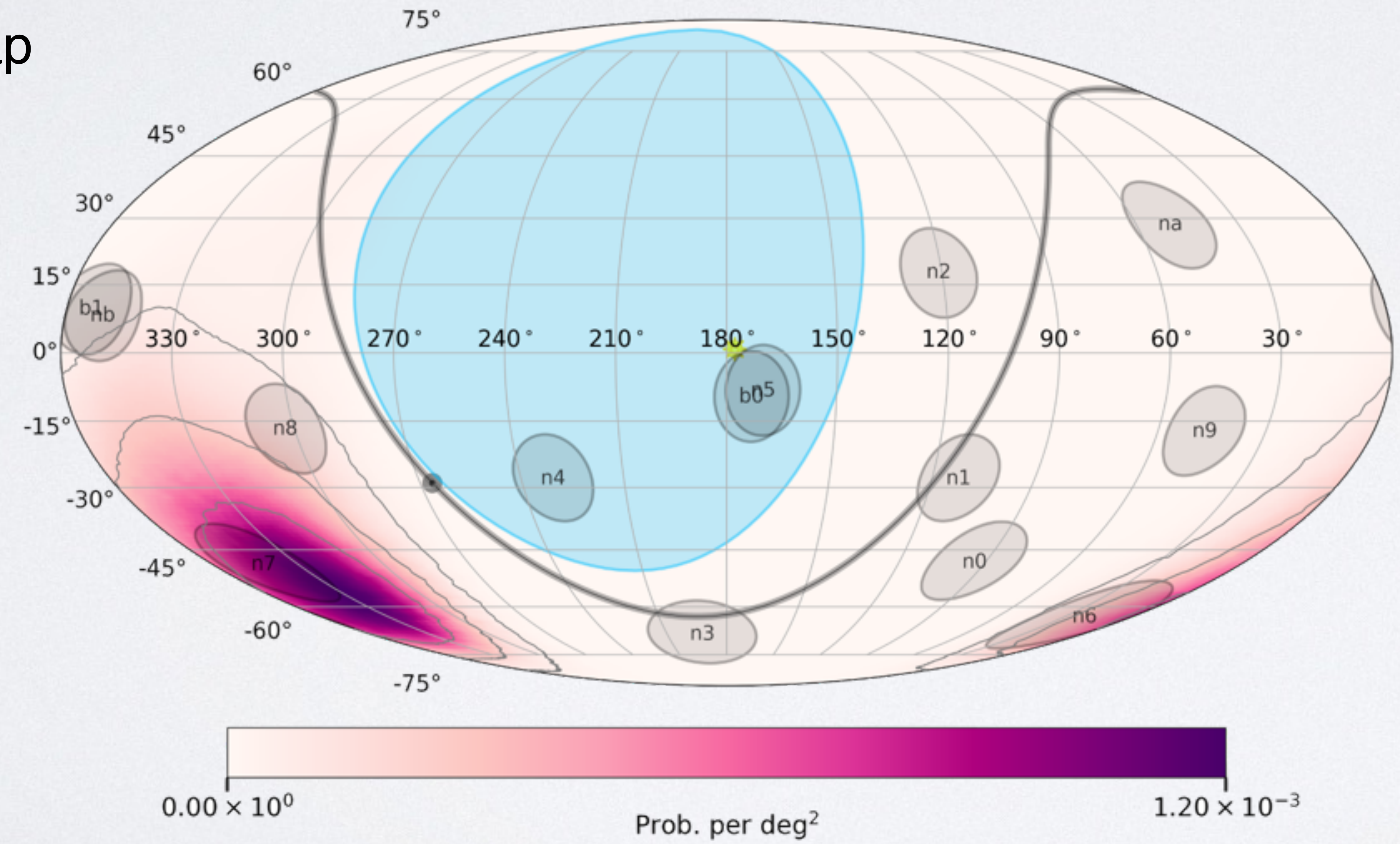
- From April 2017 to now, **64/month**, excluding Oct/Nov 2017
  - Found additional burst-like transients from magnetars and X-ray binaries
- **GRB170817A: could dim x0.5 and still recover by untargeted search.**



- 318 short, hard candidates found in 46 months in previous study —> ~80 per year.

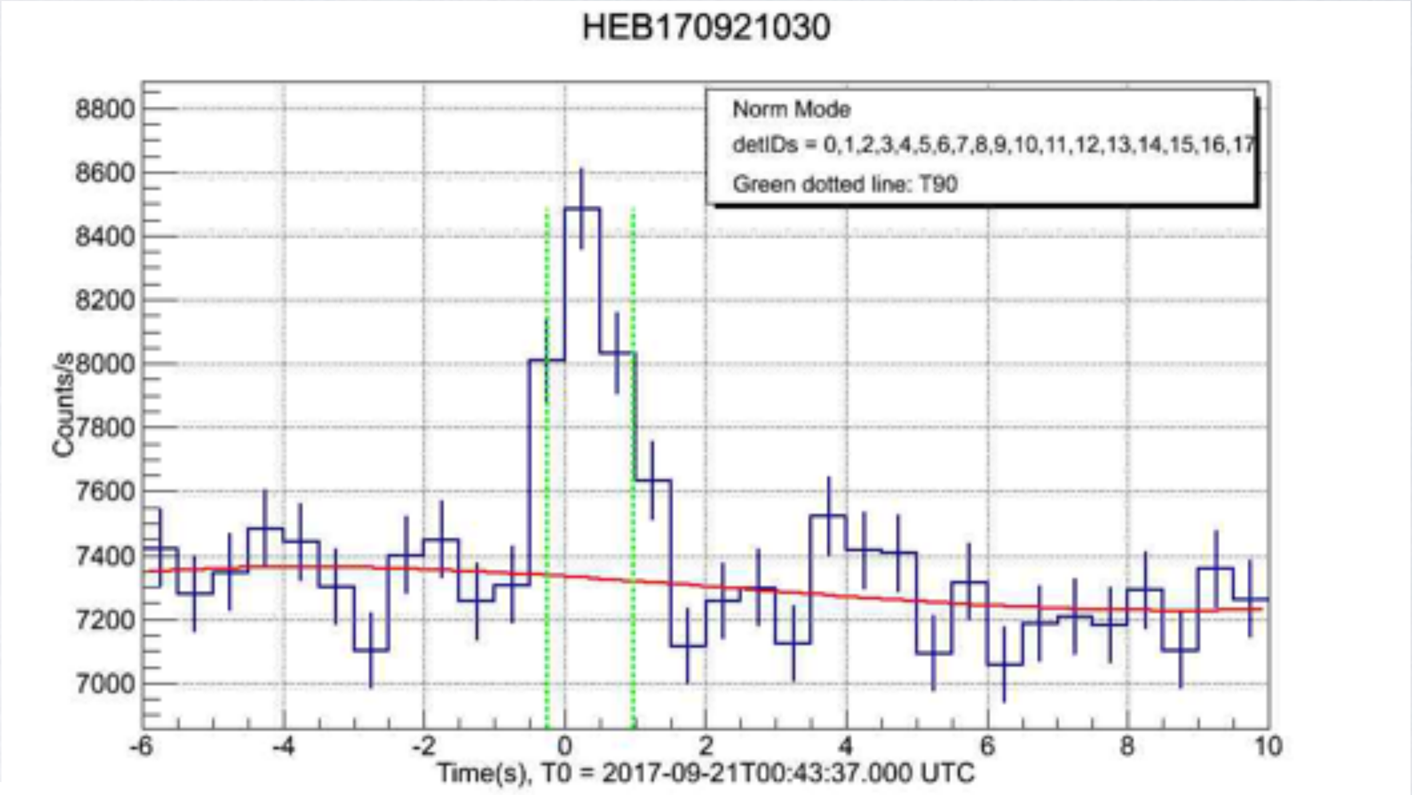
UNTARGETED SEARCH

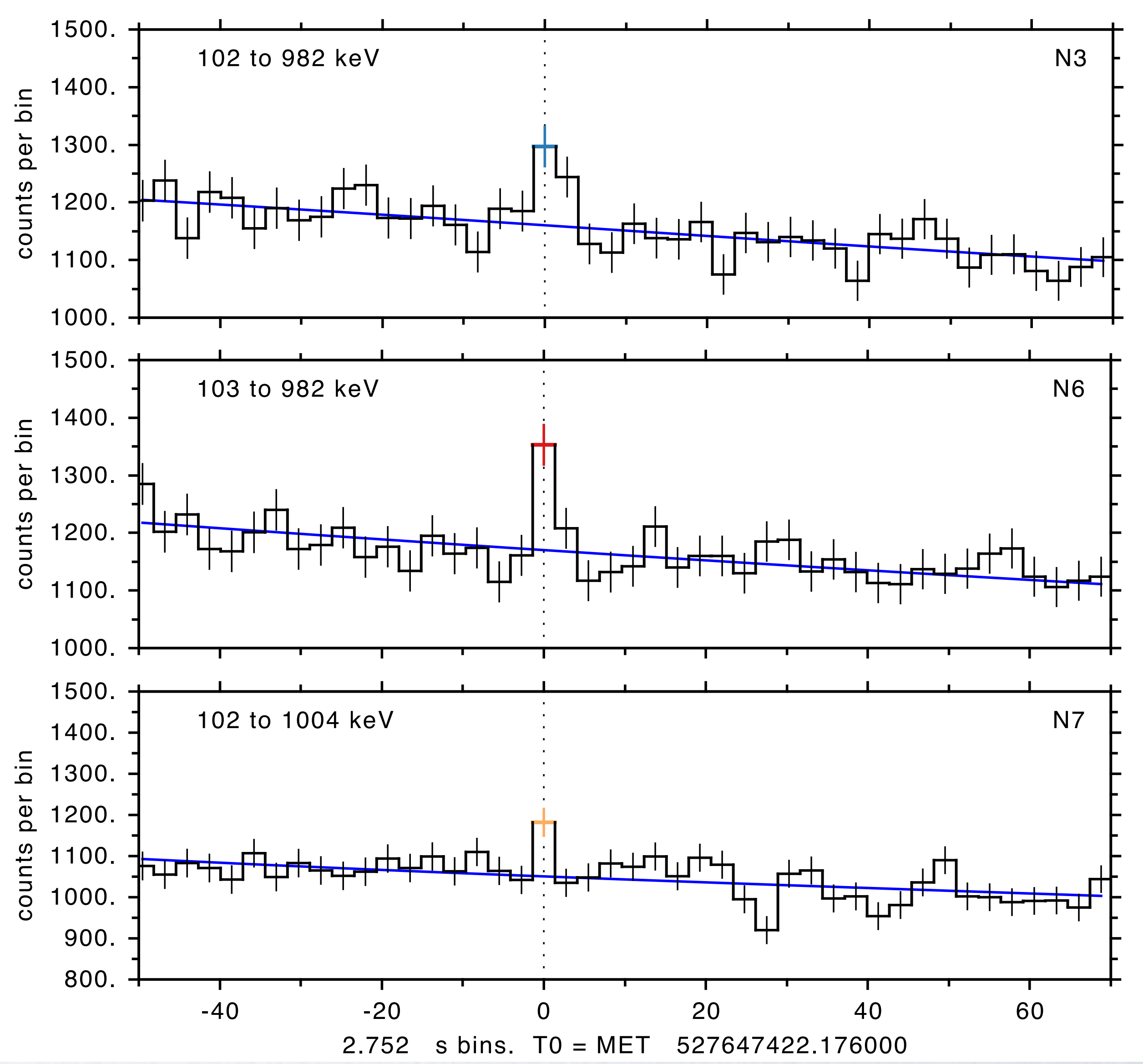
- GCN notice type Fermi-GBM SubThreshold now available. https://gcn.gsfc.nasa.gov/fermi_gbm_subthreshold.html
- Time delay for notice range from 0.5 to 6 hours, due to telemetry schedule.
- List of candidates from older data (2013 and on) are available. http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html
- Available with the GCN notice:
  - Localization FITS file
  - Contour sky map
  - Lightcurve



GRB 170921C [Zhang et al. GCN 21919]

- Insight-HXMT 12σ detection coincident with Fermi-GBM subthreshold transient 527647422.



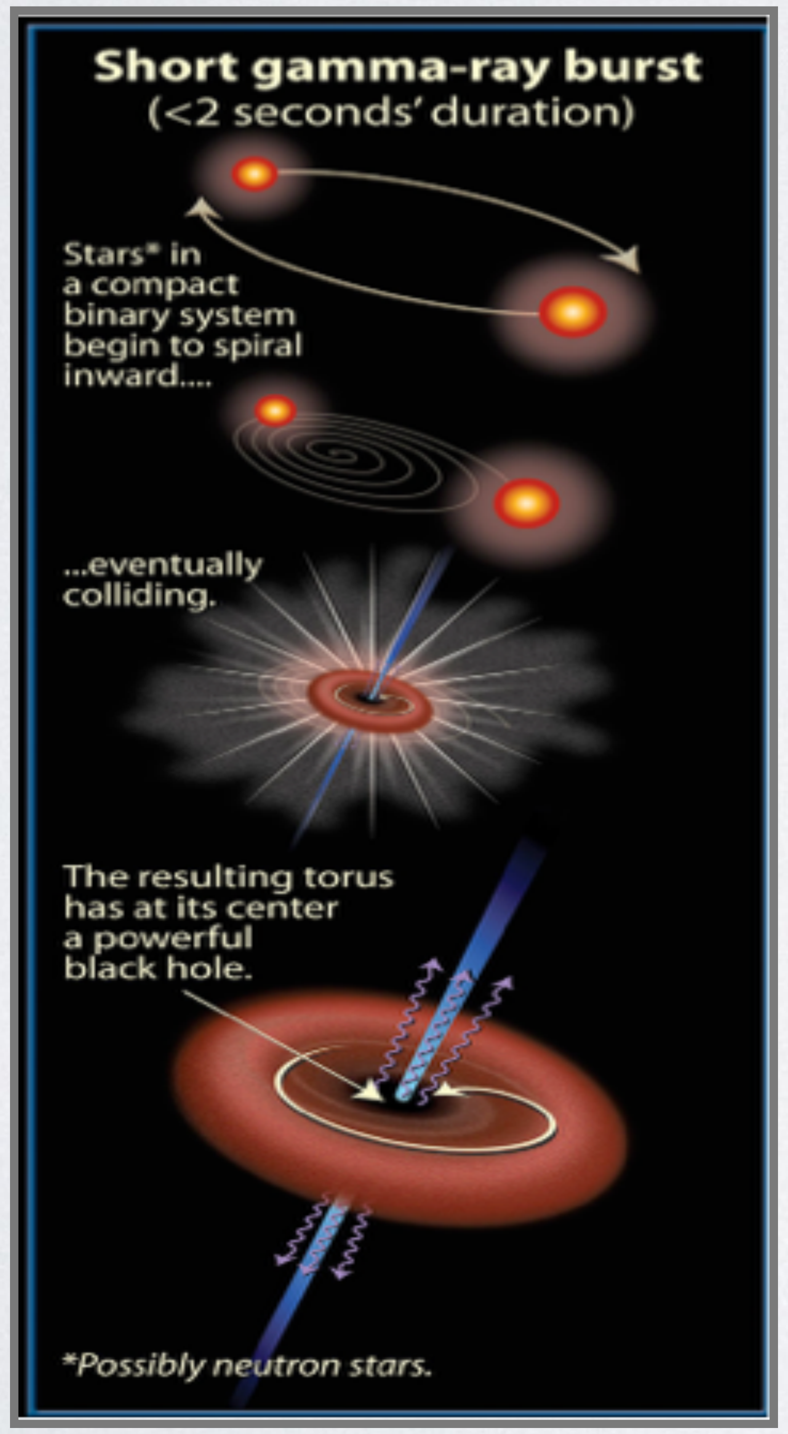


GROUND SEARCH PIPELINES

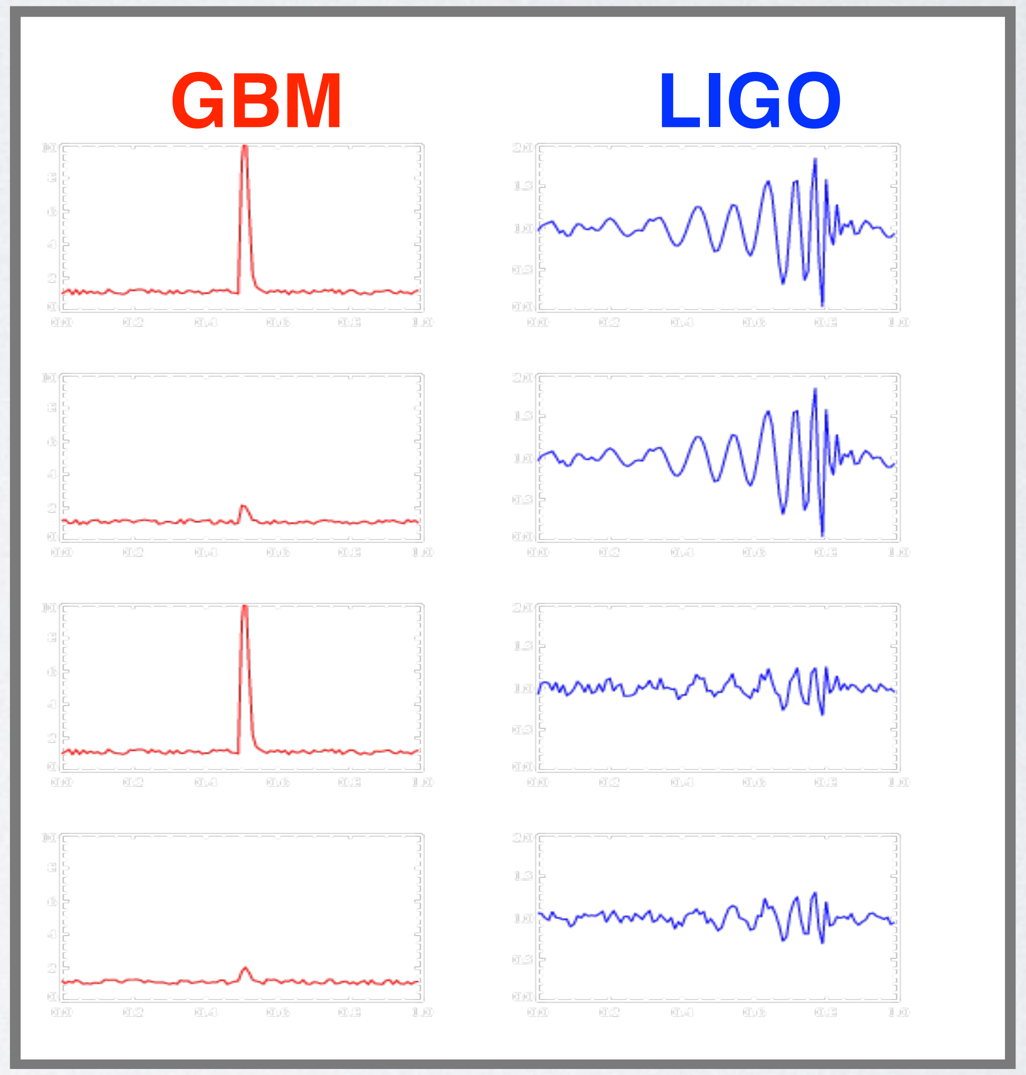
- Continuous Time Tagged Events (CTTE) enabled 2012
  — 2μs, 128 energy channels

1. Untargeted search for subthreshold GRB candidate events

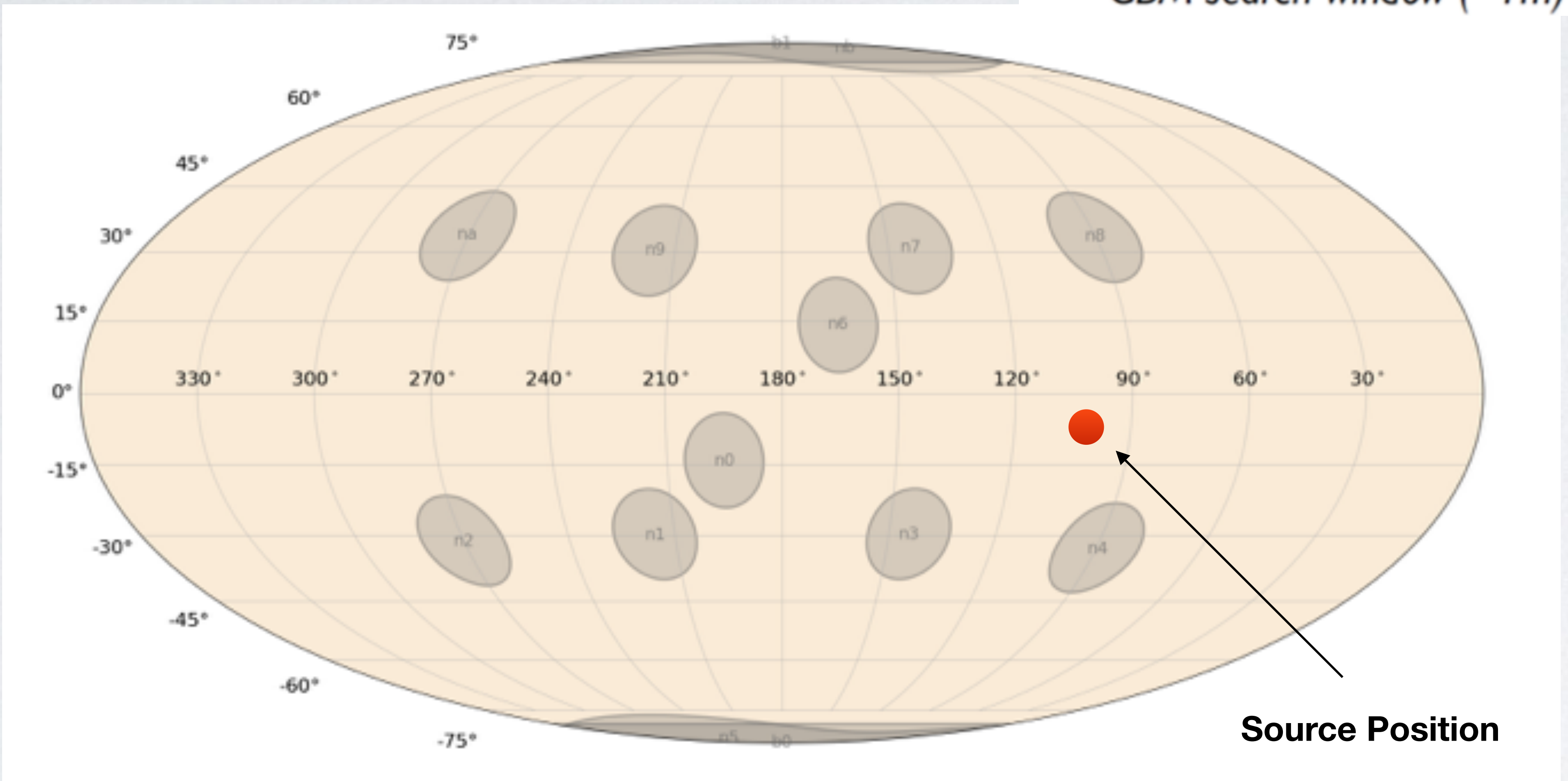
2. **Targeted search using input event time and optional skymap**



Ideal Scenario	Bright GBM	Bright LIGO
GW150914 Scenario	Sub-threshold GBM	Bright LIGO
Typical more distant short GRB	Bright GBM	Sub-threshold LIGO
Both Sources Faint	Sub-threshold GBM	Sub-threshold LIGO



TARGETED SEARCH



background-subtracted counts

response

source amplitude

product over independent observations (detectors/ energy channels)

likelihood including signal model

$$P(d_i|H_1) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_{d_i}} \exp\left(-\frac{(\tilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2}\right)$$

likelihood from noise only

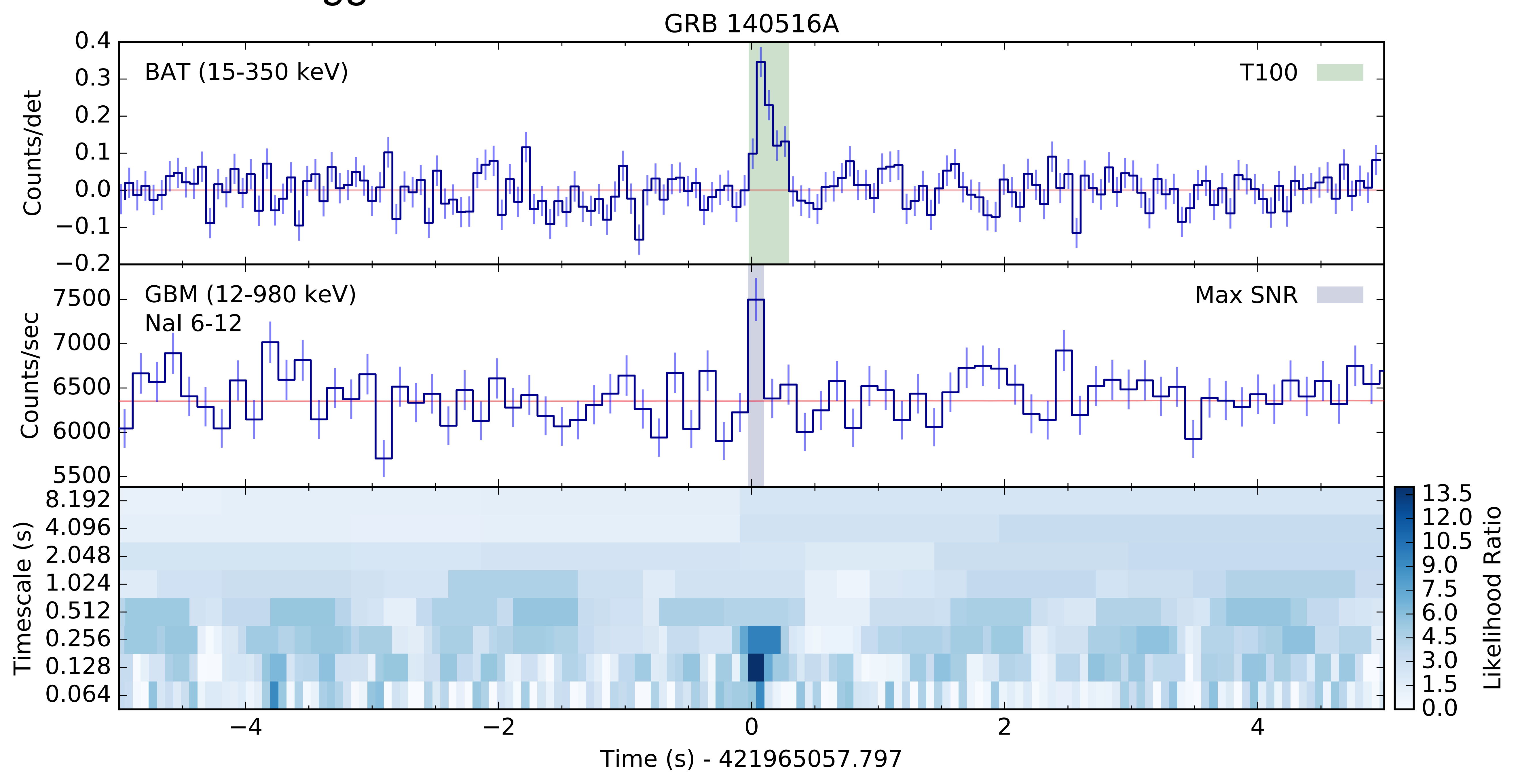
$$P(d_i|H_0) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_{n_i}} \exp\left(-\frac{\tilde{d}_i^{\,2}}{2\sigma_{n_i}^2}\right)$$

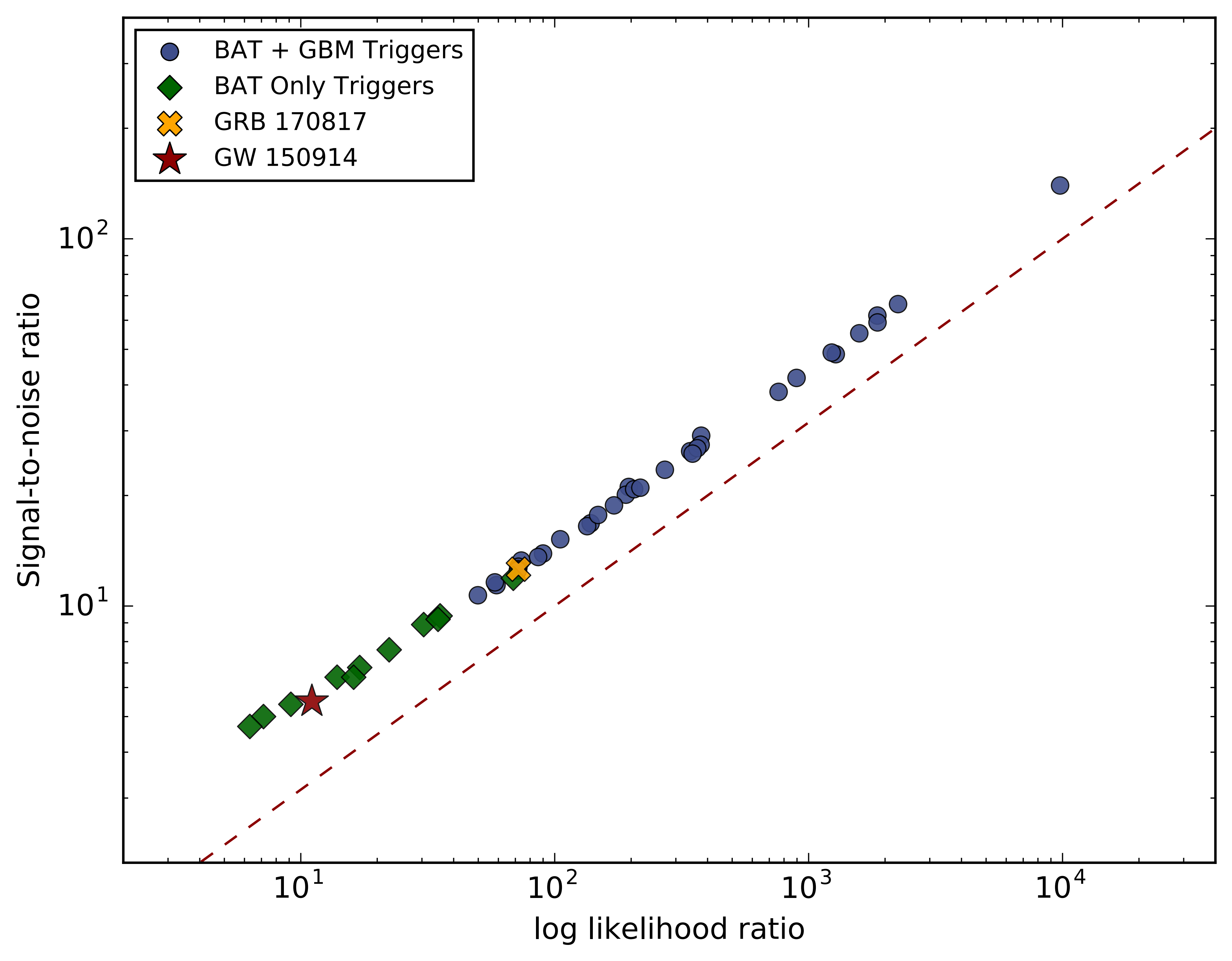
- **Targeted** search in the Continuous Time Tagged Events (CTTE) data. (Blackburn et al. 2015, Goldstein et al. arXiv:1612:02395)
  - Looks for coherent signals in all detectors given an input time and optional skymap.
  - Calculate likelihood ratio of source and background.
  - Search +/- 30 seconds of input event time.
  - Sliding timescales from 0.256s to 8s (capable down to 0.064s) with a factor of 4 phase shift.
  - 3 source spectral templates using Band function: soft, normal, and hard.

TARGETED SEARCH

- Testing with a control sample: 42 short GRBS detected by Swift BAT also in GBM FOV (2008 Aug 4 — 2017 Aug 4)
  - 31 detected by both instruments
  - 11 only by Swift
    - intrinsically dim and/or poor viewing geometry by GBM

Swift GRB did not trigger GBM





40/42 detected by the targeted search at >3σ (likelihood ratio >9)

Kocevski et al. 2018

TARGETED SEARCH

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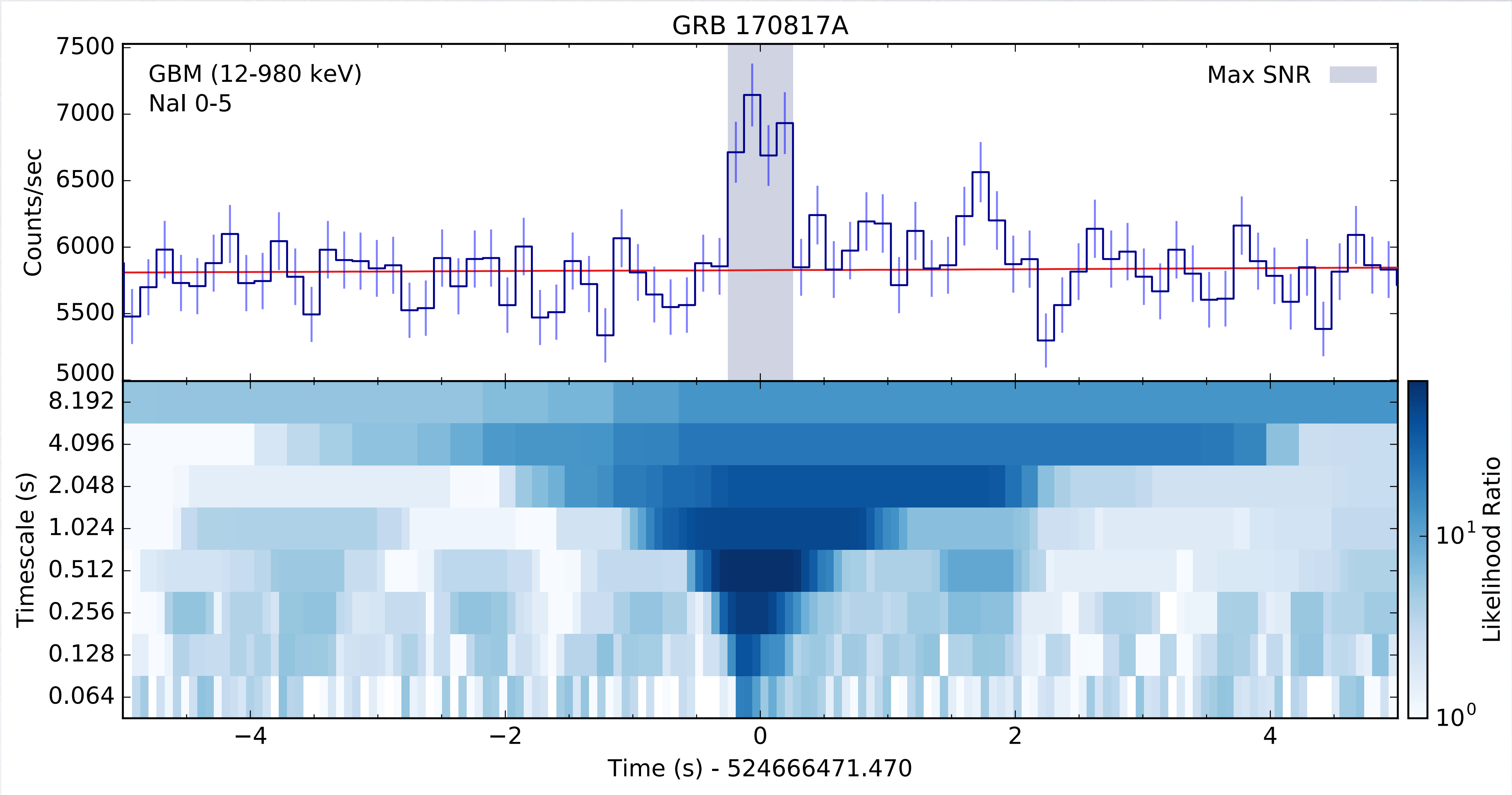
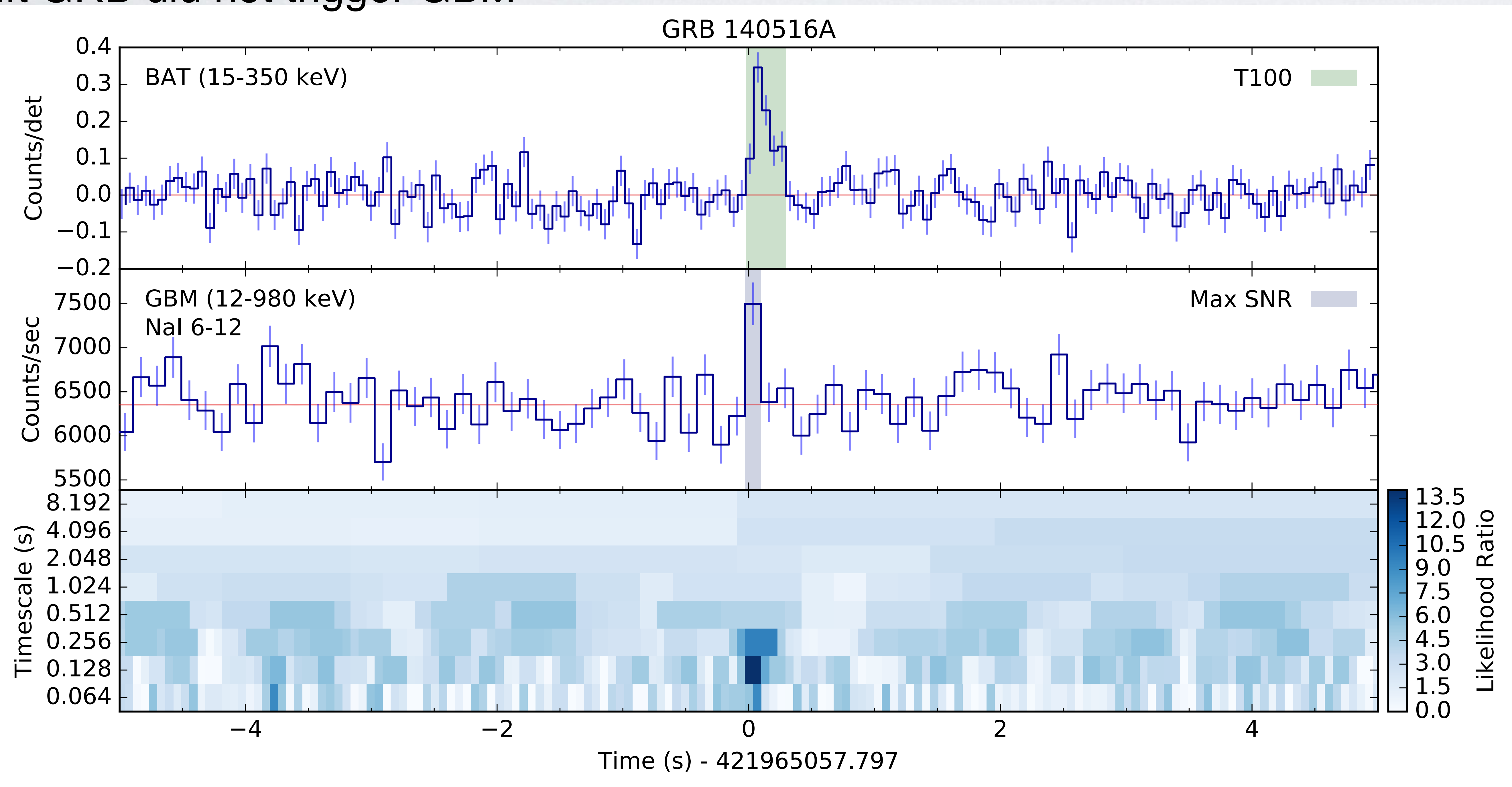


Swift GRB did not trigger GBM



GRB 170817 can dim by 60% and still discoverable by this search

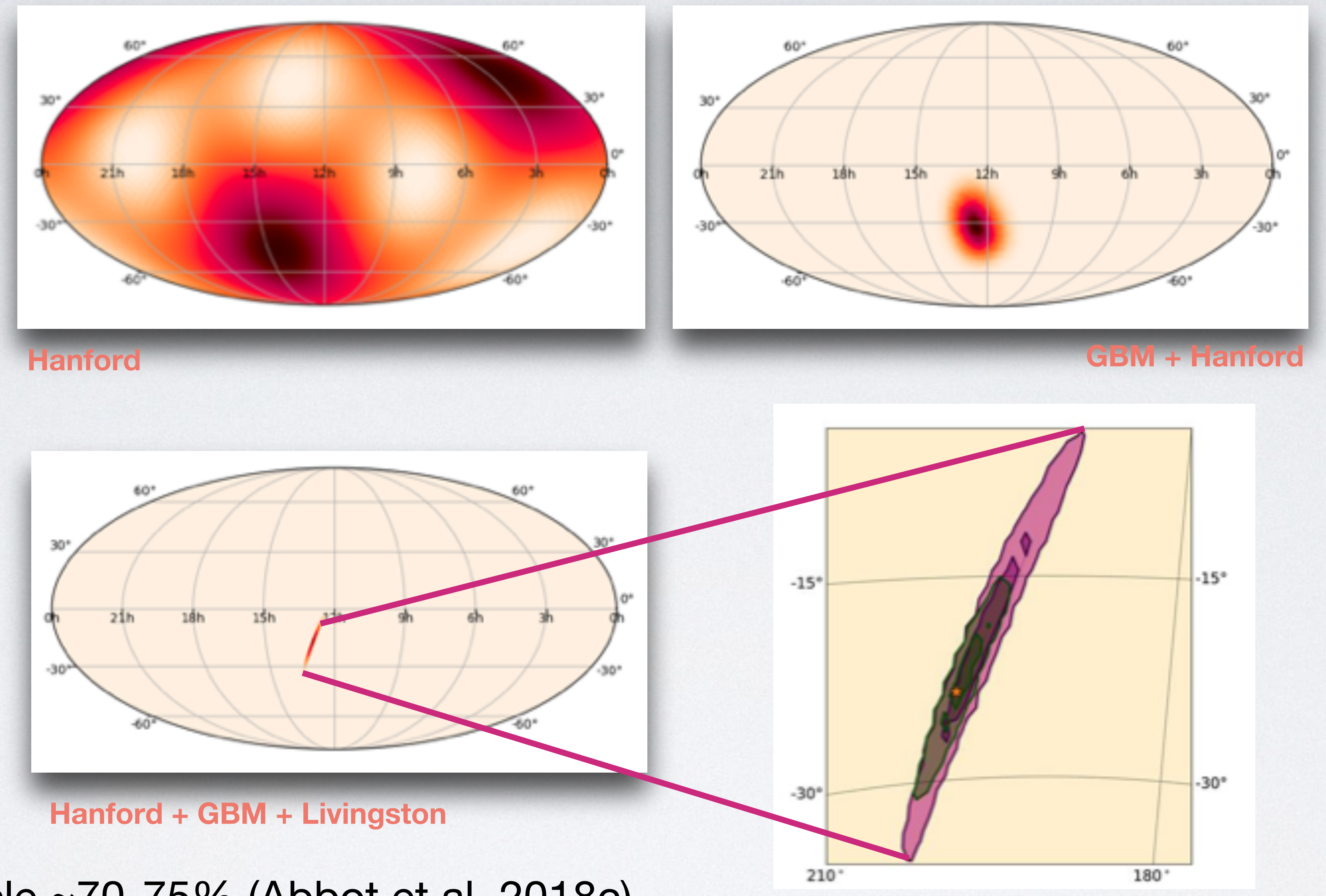
-> increases the volume of the Universe in which GRB 170817 could be detected by factor of 5

Kocevski et al. 2018

GBM-LIGO PARTNERSHIP

- GBM-LIGO MoU allows for a unique data sharing agreement
- GBM provides sub-threshold GRBs in low-latency for GW follow-up
- LIGO provides “sub-threshold” GW candidates below EM Follow-up threshold
- In low-latency for autonomous targeted searches with GBM
- GBM detections would provide increased confidence in weak GW detections, effectively increasing the volume of the Universe accessible to LIGO/Virgo

GBM-LIGO PARTNERSHIP



- GW duty cycle ~70-75% (Abbot et al. 2018c)
    - 3 (2) GW detectors operating 34 – 42% (78 – 84%) of the time
    - GBM will often constrain single interferometer localizations
- For GRB 170817A, GBM+HL map (~60 sq. deg) could have been produced ~1 hr after GW trigger

SUMMARY

- GW170817 / GRB 170817A is one of the best observed transient and highlights the science impact of multimessenger observations.
- Many open questions remain, with increased GW interferometer sensitivity, there will be more joint detections with GBM, enabling deeper population studies of SGRBs:
  - Additional distance measures which yield source energetics
  - Constrain jet structure and opening angle distribution
  - Cocoon emission from SGRBs
  - Causes of precursor and extended emission
  - Rates of SGRBs in the universe with implications for source evolution
- Fermi GBM is currently the most prolific short GRB detector
  - Subthreshold searches are crucial to increasing GBM sensitivity and the detection horizon to weak events like GRB 170817A
- Looking forward to future multimessenger discoveries:
  - Neutron star — Blackhole merger, neutrinos, Fast Radio Bursts!?